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COLOR FLAT PANEL DISPLAYS: 3D AUTOSTEREOSCOPIC BRASSBOARD AND FIELD SEQUENTIAL ILLUMINATION TECHNOLOGY

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DTI has advanced autostereoscopic and field-sequential color (FSC) illumination technologies for flat panel displays. Using a patented backlight technology, DTI has developed prototype 3D flat panel color display that provides stereoscopic viewing without the need for special glasses or other viewing aids. The effort encompassed the adaptation and advancement of a basic parallax illumination concept into a system that repositions the viewing zones in response to viewer head movement. This technique involves real-time variable positioning of the stereo viewing zones and provides wide angle autostereoscopic viewing. Discussions of system architecture, critical component specifications and resultant display characteristics are provided. Also researched was a unique FSC illumination technique involving a combination of colored illumination patterns that are sequentially imaged within the pixels of an LCD. A breadboard model of this illumination system has been built and clearly demonstrates the techniques ability to produce color at reduced frame rates without flicker visibility or color breakup. A description of the concept, breadboarding effort and data supporting claims are provided.

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SYMBOLS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
AR	anti-reflective
cd/m^2	candelas per square meter
CRT	cathode ray tube
DTI	Dimension Technologies Inc.
fc	foot candles
fL	foot lamberts
fps	frames per second
FSC	field-sequential-color
LC	liquid crystal
LCD	liquid crystal display
RGB	red, green, blue
SBIR	Small Business Innovation Research
SGI	Silicon Graphics Inc.
TFT	thin film transistor
VGA	video graphics adapter
WPAFB	Wright-Patterson Air Force Base
XGA	extended graphics adapter

SUMMARY

This contract between Wright-Patterson Air Force Base (WPAFB) and Dimension Technologies Inc. (DTI) covered both the development of a 3D flat panel color autostereoscopic display and an extended research and development effort resulting in the production of a breadboard which embodies DTI's field-sequential-color (FSC) illumination technique.

In August 1989, Dimension Technologies Inc. (DTI), proposed the development of a prototype flat panel color autostereoscopic display based on its patented parallax illumination technology in response to a solicitation, 3D FLAT PANEL COLOR DISPLAY PRDA 89 9 PMRN, issued by WPAFB. This solicitation recognized the benefits of 3D viewing for situational awareness, but found other stereoscopic technologies, which utilize special glasses or viewing aids, to be unacceptable for cockpit application. In addition, WPAFB identified critical space, power and luminance requirements associated with cockpit applications. Issues which DTI could address favorably because its technology is liquid crystal display (LCD) based.

In August 1993, DTI delivered a cockpit prototype display system to WPAFB, which provides an effective demonstration of autostereoscopic display technology for advanced cockpit display applications.

The kernel of DTI autostereoscopic technology is a patented LCD backlight technology called **parallax illumination**. The technique, which was proven prior to this program, utilizes a precision illumination array located behind the LCD pixels. The relationship of the illuminator to the LCD pixel elements effectively creates discrete image viewing zones in front of the display. In each zone, either a left or right perspective image can be seen. The zones repeat laterally in front of the display and alternately contain left and right images. Therefore, when a viewer is positioned with their left eye in a left image zone, and their right eye in a right image zone, a stereoscopic image is perceived.

Because this basic approach creates fixed viewing zones, it restricts a viewer's ability to freely move in front of the display. To overcome this limitation, DTI proposed to extend the basic parallax illumination concept into a system which would dynamically reposition the viewing zones in response to viewer head movement. This technique, called **dynamic parallax illumination**, involves real-time, variable positioning of the illumination behind the LCD. This allows for dynamic control of the parallax illumination and positioning of the viewing zones. When coupled with a head tracking system which measures a viewer's head position relative to the display, the system provides wide angle stereoscopic viewing.

Under the program, DTI explored two design approaches for dynamic parallax illumination. Initially, an electro-mechanical system was implemented which provided continuous variable control of the lateral position of a lens array. In a second effort, an electro-optical system was implemented which created three discrete viewing zone sets through switchable illumination. The final system delivered to WPAFB utilizes this latter approach.

The system consists of four major system segments: a DTI Dynamic Parallax Illumination system, an LCD device, a viewer head position sensor subsystem, and an image generation system. The four work together to create left and right image zones which are properly aligned with the viewer's left and right eyes across an extended range in front of the display.

During the program, DTI conducted detailed design and analysis of each subsystem to gain a clear understanding of the performance issues associated with each system segment and achieve optimal performance levels. Following system integration, careful testing was performed to validate system requirements, and gain additional understanding of critical system issues. Final system acceptance test results demonstrated conformance to nearly all the display system requirements as specified in the program contract. Items of non-conformance were addressed through demonstrations and analyses provided to WPAFB throughout the course of the program.

In conjunction with the development of the cockpit prototype system, DTI developed a prototype suitable for commercial application. Following the theme of "dual use", this effort successfully coupled the cockpit prototype efforts with DTI's product development efforts. The result has been a quick and effective application of defense-oriented research for commercial purpose. The commercial prototype system has provided the foundation for DTI's current product development. DTI is now selling small quantities of prototype displays for evaluation purposes in application areas such as: medical imaging, telerobotics, avionics, and stereo microscopy. This is setting the stage for the development of a high performance, low cost autostereoscopic display system which can be applied in a variety of commercial markets.

The advancements made at DTI under this portion of the program have been significant. The experience gained by these efforts has provided practical knowledge which will be critical in the further development of an autostereoscopic display suitable for military and commercial application. The systems developed provide the necessary means to demonstrate the utility and effectiveness of stereoscopic imaging. To date, the use of stereoscopy has been limited because of the requirement for special glasses or other obtrusive viewing devices. DTI has proven its autostereoscopic display technology can overcome this barrier. What lies ahead is further refinement and application of the technology in order to realize the full potential demonstrated by the results of this program.

In March 1993, the scope of the contract was extended to include research into a unique field-sequential-color illumination technique and development of a breadboard demonstrating the technique and its performance claims of reduced frame rates, flicker visibility and elimination of color breakup.

The Air Force had been investigating FSC techniques as a means to achieve improved resolution and luminance with flat panel displays. Conventional approaches to field-sequential-color illumination produce color images by sequentially illuminating a fast 180 fps monochrome LCD with red, green, and blue light. Previous field-sequential-color devices have been unusable for avionics applications because of a phenomena called color breakup which is evident during rapid eye shifts or vibrations.

As an outgrowth of advanced autostereoscopic developments, DTI devised and experimentally validated a technique for producing FSC LCDs. The technique involves a combination of colored illumination patterns that are sequentially imaged within the pixels of an LCD. The technique in theory would eliminate the color breakup phenomena, lessen the LCD speed required for flicker-free imaging, and retain the other advantages associated with field-sequential color.

A breadboard model of this illumination system was built under this program to evaluate it's ability to produce a color display, and support evaluations of flicker performance, color breakup visibility, illumination luminance and evenness and overall system efficiency.

The breadboard which uses a monochrome AMLCD, clearly demonstrates the techniques ability to produce color and supports claims of reduced frame rates, flicker visibility and elimination of color breakup.

This work can lead to a superior means of producing color displays using monochrome LCDs. Application of the research by LCD manufacturers may allow that industry to produce simplified, less costly LCDs for color displays.

SECTION A - 3D FLAT PANEL COLOR DISPLAY

1. INTRODUCTION

1.1 Stereoscopy

Stereopsis

We are endowed with binocular vision and naturally see our environment in 3D; thus, adding the third dimension to displayed images greatly enhances our ability to perceive and interpret certain types of imagery. This is especially true in applications where spatial relations of objects need to be interpreted rapidly, accurately and instinctively; for instance, in controlling a remote vehicle, flying an aircraft, or identifying targets with a FLIR system.

The perception of 3D or stereopsis depends on the phenomenon that our left and right eyes see slightly different images which are fused in the brain into one image that has the quality of three-dimensionality. All current commercial 3D display systems function by taking advantage of this natural process in that they present each eye with a different image which the brain then interprets as being three-dimensional.

The 3D imaging technologies on the market or in development now can be broadly divided into two categories: stereoscopic and autostereoscopic. The difference between them is that the former requires the user to wear glasses or look through other optical devices positioned at the eye in order to perceive 3D, while the latter generates three-dimensional images which can be seen without optical aids, an obvious advantage in many circumstances.

Stereoscopic Displays

Stereoscopic electronic display products have been on the market in one form or another for many years. Currently the most popular professional versions are made by New Vision (formerly manufactured by Tektronix) and Stereographics Corporation. Both manufacture glasses and related devices that can be used with suitable CRT monitors to provide stereoscopic images.

The New Vision and Stereographics systems utilize different technologies to implement the presentation of proper images to the two eyes. Both rely on the alternate display of left and right eye images of a stereo pair sequentially on a CRT, but fast enough so that the threshold of the fusion frequency is exceeded, thus eliminating flicker. New Vision changes the direction of polarization in a special liquid crystal (LC) screen placed in front of the CRT to make the correct images visible to the right and left eye of the user, who wears passive polarizing glasses of the same generic type used in movie theaters.

Stereographics utilizes glasses equipped with remotely controlled electro-optical shutters operating in synchronism with the presentation of the left and right halves of a stereo pair on the CRT.

In addition to requiring the user to wear glasses, both systems have the disadvantage of reducing the luminance of the images introducing some discoloration. In addition, none of the stereoscopic systems requiring glasses approach conventional 2D displays in terms of convenience and ergonomic factors such as ease of use and comfort.

Autostereoscopic Displays

Considerable research and development activity has been aimed at devising autostereoscopic displays which would present bright, high quality color hologram-like 3D images that one could see simply by sitting in front of the display and looking at it, and not have to wear any special glasses or viewing aids.

In 1990, DTI introduced the world's first flat panel autostereoscopic display product using a monochrome LCD and the company's proprietary autostereoscopic lighting and optical technology. During the same year, DTI began the development of the 3D Flat Panel Autostereoscopic Color Display, which is the subject of this report.

1.2 Autostereoscopic Display Through Parallax Illumination

The heart of DTI autostereoscopic technology is a unique LCD backlight technology which is called **parallax illumination**. Figure 1 illustrates the basic concept and Figure 2 further illustrates the geometry of the system.

As shown in Figure 1, the system employs a transmissive image forming display, such as an LCD, situated in front of, and spaced apart from, a special illumination plate. The illumination plate produces a large number of thin, bright vertical illuminating lines, with a dark space between each. There is one line for every two columns of pixels. The lines are spaced such that an observer sitting an average viewing distance in front of the display sees all of the light lines through the odd columns of pixels with his or her left eye, and the same set of lines through the even columns with his or her right eye.

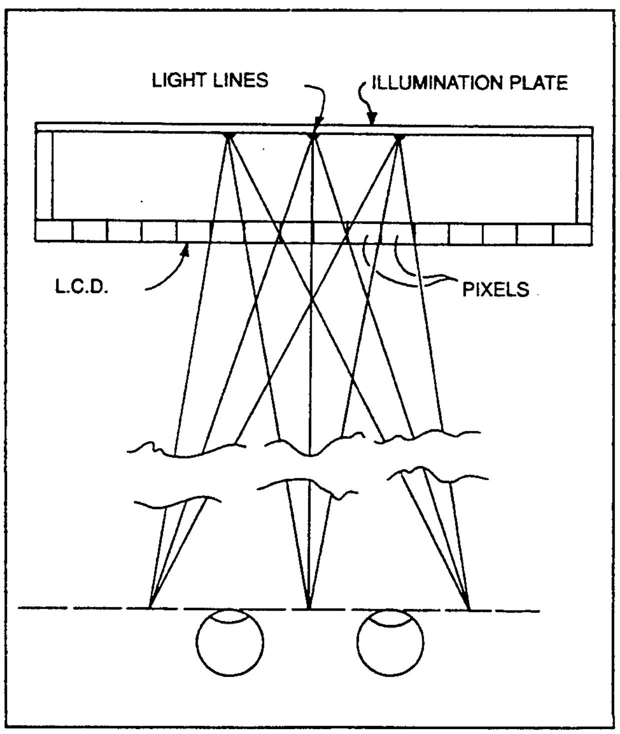

Figure 1
The Parallax Illumination Concept

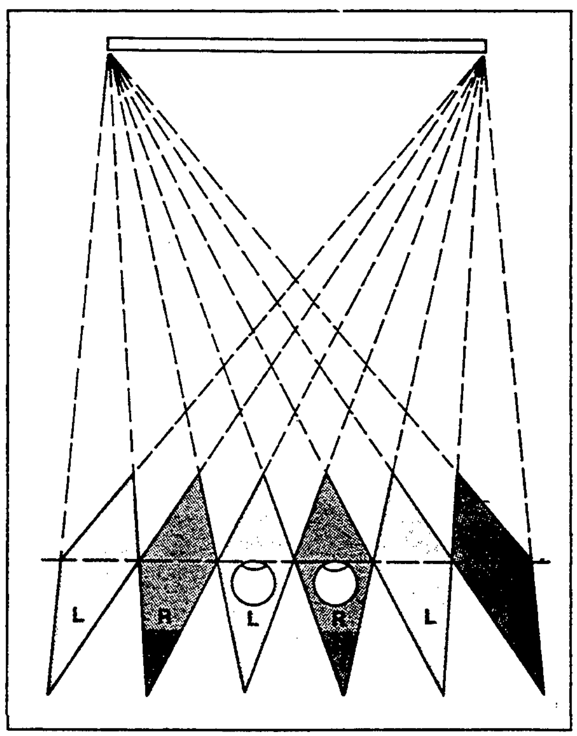

Figure 2
Viewing Zone Structure

Since the display is transmissive, the information on any pixel can be seen only when illumination is seen behind the pixel. Thus, the observer's left eye sees only the information on the odd columns of pixels, and his or her right eye sees only what is on the even columns. To produce a stereoscopic image, one must display the left eye view of a stereo pair on the odd columns, and a right eye view on the even columns.

In Figure 2, a left eye view is seen anywhere within the quadrilateral shaped areas marked L. and a right eye view is seen anywhere within the areas marked R. As can be seen, there are several left and right eye viewing zones in front of the display. These zones are all widest at a certain plane that is parallel to the display surface and is situated at the most comfortable viewing distance from it. The distance of this optimal viewing plane is determined by the distance of the light lines from the LCD.

The positioning of the lines can be calculated with simple geometry in a two step process. First, the spacing between the lines and the pixels should be calculated. To do this, one must consider both the optimal viewing distance and the width of the viewing zones, the regions of space where one sees a left eye or a right eye image, at the optimal viewing distance.

The ideal width of the viewing zones at the widest point is 6.3 cm, the average distance between a person's eyes. This width gives the average person the greatest freedom of head movement from side to side. As can be seen in Figure 3, a number of left eye and right eye zones are present, with thin dead zones between them. In these zones, the light lines are all seen behind the spaces in between the pixels. Increasing the zone width also increases the width of the dead zone, and thus narrows the distance which the person can move left or right before one of their eyes crosses into a dead zone.

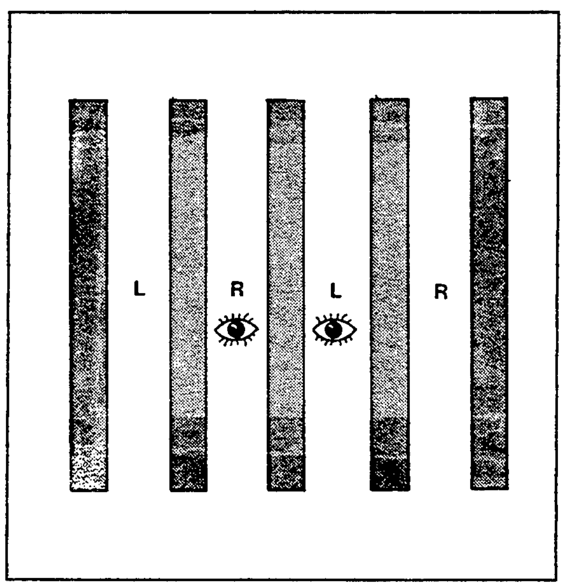

Figure 3
Viewing Zones Shown With Dead Zones

Likewise, narrowing the zone widths also narrows the dead zone widths, but moves the dead zones at the outer edges inward, so that again the distance that the person can move before one of their eyes crosses the outer edge dead zones is narrowed. Thus for any given observer, it is best to have zones that are equal in width to the center to center distance between his or her pupils. This distance is on the average 6.3 cm, and seems to provide a comfortable zone for most normal adults.

The designer must specify the ideal viewing distance for the particular display. A typical viewing distance is about 76 cm, but depending on the screen size and application, this could vary. In any case the spacing between the lines and the pixels can be calculated through simple geometry from Figure 1:

S = the illuminating line pitch

P = the pixel width

D = the optical distance between the illuminating lines and the pixels of the transmissive display.

V = the viewing distance

Because of similar triangles:

$$P/D = 6.3/(V+D)$$

or

$$D = (V \times P)/(6.3-P)$$

Next, given this distance, the pitch between the illuminating lines can be calculated again by simple geometry. It can be proven by similar triangles method that:

$$S/(V+D) = 2P/V$$

or

$$S = 2P(V+D)/V$$

This formula shows that the distance between adjacent illuminating lines is equal all the way across the illumination panel, and that this distance is slightly greater than twice the pitch of the display pixels.

There are many ways to produce a series of thin, bright lines on a black background. Two of the methods that DTI has developed are described in detail later. They both involve the use of optics to generate hundreds of tiny light lines using the output of a small number of linear lamps.

Looking at non-stereoscopic images with the 3D illumination on can be annoying, since each eye sees different pixel columns of the same image. In the case of text, for example, each eye sees different parts of each letter. A 2D viewing feature is therefore very important in applications where one display must be used for several applications, and not just stereo viewing. One versatile aspect of this illumination arrangement is that it can be used for full resolution 2D as well as 3D viewing simply by changing the

illumination so that even, diffuse light is turned on behind the LCD, instead of the light lines. Then the observer's eyes will see all the pixels as with any other LC display, and the observer can use the system at full resolution for conventional 2D applications. There are several possible ways to do this, as discussed later.

1.3 The Head Tracking Concept

The static viewing zones created by the basic parallax illumination method described above, impose a restriction on viewer position and freedom of movement. Therefore, DTI has extended this capability in a technology which is called **dynamic parallax illumination**. This technique involves real-time, variable positioning of the light lines behind the LCD. This allows for dynamic control of the parallax illumination and positioning of the viewing zones. When coupled with a head tracking system which provides measurements of a viewer's head position relative to the display, the system can yield a completely unobtrusive stereo display with a wide angle viewing range.

As can be seen from Figure 2, the observer's head must be placed within certain position ranges in order to see 3D. When the observer is a pilot in a cockpit, for example, such head position restrictions are impractical. Therefore, DTI developed concepts for head tracking in order to eliminate the head position restrictions within a defined area.

Head tracking involves the use of a head position sensor to determine the position of the user's head at all times. Methods are employed to move the viewing zones to follow the observers head and stay centered on the user's eyes. Head position sensing can be accomplished by several means, including ultrasound, infrared, and the sensing of an electro-magnetic emitter mounted on the head.

Viewing zone movement can be accomplished by moving the light lines laterally in response to head position information given by the head position sensing device. As the light lines move, their position relative to the pixel boundaries changes, and therefore the position of the viewing zones change. The light line movement can potentially be accomplished by either physically moving the optical device that generated the light lines, or in some cases, by simply turning different sets of light sources on and off.

1.4 Program Objectives

Wright-Patterson Air Force Base, recognizing the benefits of 3D viewing for situational awareness, issued a solicitation requesting development of a 3D flat panel display. In response to 3D FLAT PANEL COLOR DISPLAY PRDA 89 9 PMRN for Wright Research and Development Center, Cockpit Integration Directorate, Crew Systems Division, DTI proposed to develop, test and deliver a prototype color autostereoscopic display using the illumination technology described above. The display would be a color TFT display capable of displaying images at video rates.

Under the final terms agreed upon in the contract, the following display properties were specified:

Table 1
Display System Requirements

Property	Requirement
Viewing Area	161 square centimeters minimum
Color	At least 8 colors
Luminance	171 cd/m^2 (50 fL) minimum with a goal of 514 cd/m^2 (150 fL).
Contrast Ratio	20:1 min in 100 fc ambient, 4:1 min in 10,000 fc ambient with a goal of 7:1, at 23 ±5 degrees C at optimal viewing angle.
Non-uniformity	Luminance and contrast non-uniformity less than 30%
Dimmability	250:1 min with a goal of 1000:1
Power Consumption	A goal of less than 200W input to the illuminating system.
Features	Switchable 2D and 3D display modes. Head tracking capability
Interface	Accepts RS-170 input.
Packaging	Maximum 2.54 cm border on all sides and a maximum 15.24 cm depth.

These specifications reflected an extension of the capabilities of an already existing technology developed by DTI. These extended capabilities included: its application to a color display; an improved, brighter illumination system; 2D/3D capability; and improvements on head tracking concepts then under investigation at DTI. The risk involved was judged to be moderate.

2. SYSTEM DESIGN OVERVIEW

To achieve 3D display across a wide viewing angle without the need for glasses or special viewing aids, DTI designed a head tracking display system. The system consists of four major system segments: a DTI Dynamic Parallax Illumination system, an LCD device, a viewer head position sensor subsystem, and an image generation system. The four work together to create left and right image zones which are properly aligned with the viewer's left and right eyes across an extended range in front of the display.

2.1 Dynamic Parallax Illumination System

The Parallax Illumination System encompasses the optics and light sources used behind the LCD to create 3D images. These images can be viewed, with proper perspective, from a wide area in front of the display screen. The primary function of the system is to create multiple sets of thin vertical light lines that can be varied in position behind the LCD. The required light line position is determined by the observer's head position supplied by a head tracking system. Two basic approaches are possible for achieving variable light line positions. One is to move the light line position continuously or in very fine increments to redirect the viewing zones. The other approach is to have a small number of discrete positions which can be switched between. This results in a set number of overlapping viewing zone states.

Under the program DTI explored both design approaches. Initially, an electro-mechanical system was implemented which provided continuous variable control of the lateral position of a lens array. In a second effort, an electro-optical system was implemented which created three discrete light line sets through switchable illumination. The following sections describe each of these systems.

2.1.1 Electro-mechanical

The basic design and concept of the mechanical dynamic parallax illumination system is illustrated in Figure 4. The light lines generated behind the LCD pixel layer by the parallax illumination system are formed by reimaging a small number of linear light sources via a lenticular lens sheet into a much larger number of parallel vertical lines. Nine fluorescent aperture lamps are used as the linear light sources. The lenticular lens images the light lines onto a weak diffuser behind the LCD.

The lenticular lens is mounted in an assembly which consists of two machined frames. One frame holds the lens sheet. This frame is mounted in the second frame, and has the ability to move laterally within this outer frame. A servo motor is mounted on the outer frame assembly. The servo drives a geared lead screw which is attached to the inner frame. Driving the servo motor results in a lateral movement of the inner frame, and therefore movement of the lens array. As illustrated in Figure 4, a shift in the lens in one direction results in a shift of the left/right image zones in the opposite direction.

The servo motor is controlled by an external electronics subsystem. The subsystem consists of a small microcontroller board which generates signals for direction and rotation to the servo. The microcontroller also interfaces to the viewer head position sensor subsystem. The firmware of the microcontroller interprets head position data in order to correctly position the servo.

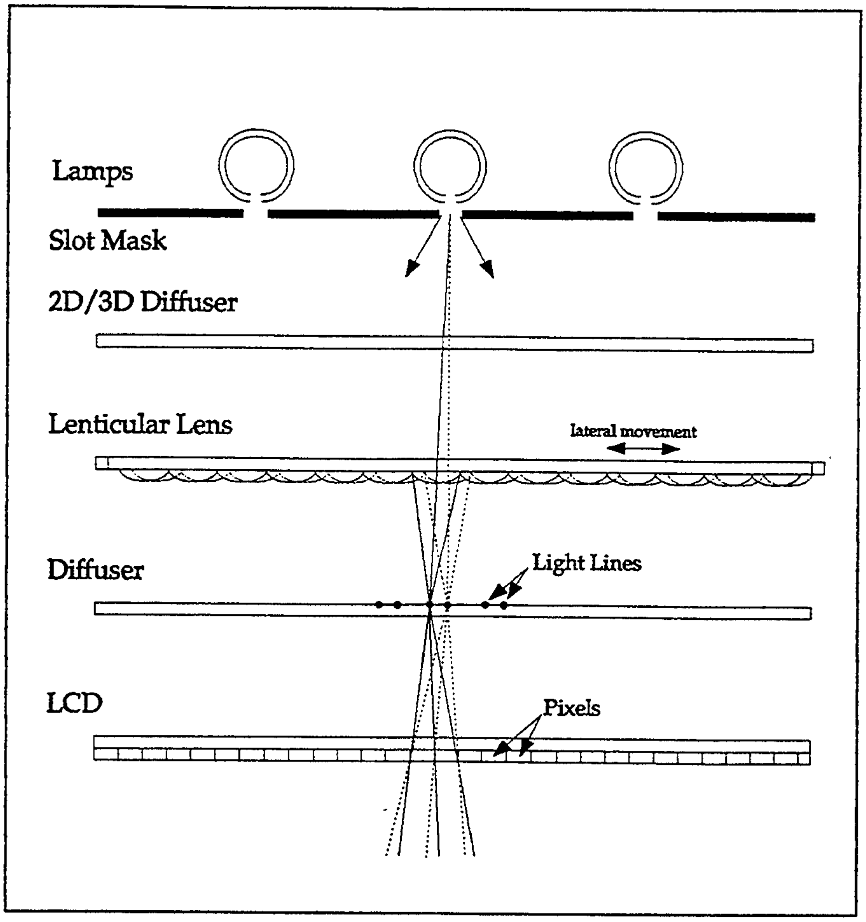

Figure 4
Electro-Mechanical Dynamic Parallax Illumination

A final element of the electro-mechanical system is a controllable LC diffuser. This component can be switched between a clear and diffuse state by varying voltage input. As shown in Figure 4, the diffuser is placed between the lamp array and the lenticular lens. When the LC diffuser is clear, the vertical light segments of the lamps remain sharp and well defined. These segments are then imaged into light lines by the lens. This results in 3D parallax illumination. When the LCD diffuser is in a diffuse state, the light segments are blurred and near uniform illumination results behind the LCD. In this state, image zones are not created, and the display can then function as a full resolution 2D display.

2.1.2 Electro-optical

As shown in Figure 5, the electro-optical dynamic parallax illumination system has many of the same components as the mechanical system. In this system, light line segments created by fluorescent aperture lamps are also imaged by a lenticular lens into a larger number of thin vertical light lines. In this system the lenticular lens array is in a fixed position. Rather than shifting light line position through mechanical means, multiple light line positions are achieved through switched illumination.

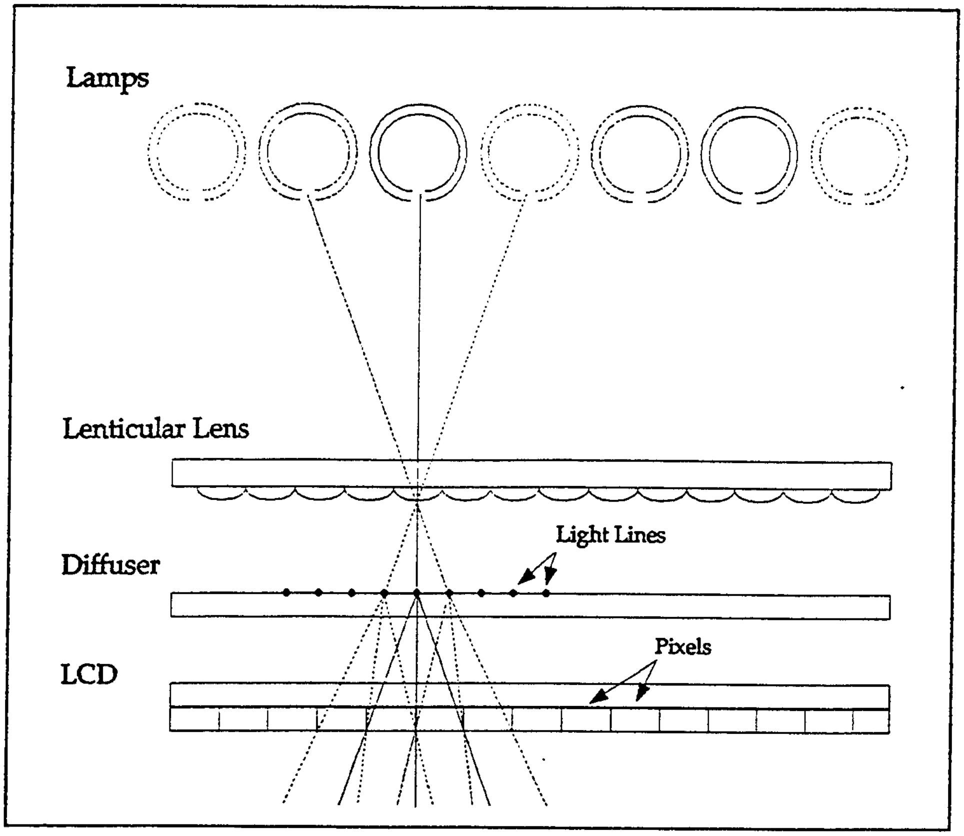

Figure 5
Electro-Optical Dynamic Parallax Illumination

Figure 5 shows three sets of fluorescent lamps. Each set, when active, results in generation of light lights at a set position. The position of the light lines is different for each set. Therefore, at any given instant, the system can create left/right image zones at one of three positions. These three viewing zone sets overlap. The sets are evenly spaced with respect to one another, so that each set, in combination with the LCD pixel columns, generates a different set of viewing zones at different positions within a viewing area in front of the display (see Figure 6).

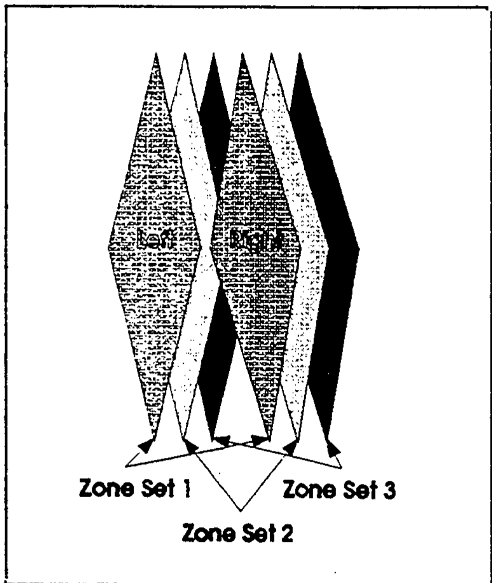

Figure 6
Electro-Optical Viewing Zones

Like the electro-mechanical system, a microcontroller device is used. In this system, it controls the lamp arrays. The viewer head position sensor device is interfaced to the controller, and firmware computes which lamp bank should be active for the current head position. During system operation, only one set of lamps is on at any given time. The active set is determined by the current viewer head position. As a viewer moves to a different position in front of the display, the current light line set is deactivated and an alternate light line set is turned on which creates viewing zones corresponding to the new head position.

As described, the system creates three viewing zone sets. Each set creates zones in which alternate pixel columns are visible. This allows for two possible positions for a viewer: one, where the left eye is seeing odd pixel columns and the right eye is seeing even pixel columns; and also the reverse, where the left is seeing even columns and the right eye odd columns. As a result, the tracking system is capable of reversing the order of the left/right images on the LCD pixel columns. This preserves proper image ordering to the viewer's left and right eyes. During head tracking operation, the images on the LCD columns are actually being swapped when a viewer moves his or her head.

A final difference between this system and the electro-mechanical is the absence of a 2D/3D LC diffuser. In this system, 2D mode is achieved by activating all three of the lamp banks. This effectively creates uniform illumination across the back of the LCD, thereby eliminating the parallax illumination effect.

2.2 LCD System

The LCD is a matrix of individually controllable elements (pixels) which are arranged in rows and columns, 480 rows and 640 columns in a 15.24 cm x 20.32 cm area. Each pixel is made up of four color elements: one for Red, one for Blue and two for Green. In 3D mode, a pixel consists of the four vertical color elements. This provides a resolution of 640 pixels horizontally by 240 pixels vertically. In 2D mode, a pixel is a 2 by 2 element square which gives a 640 by 480 pixel image. The LCD is active matrix which allows for real-time video update of images.

To properly display 3D images, the LCD places left and right images on alternate columns of pixels at a rate of 60 frames per second. The left image appears on the odd columns, while the right image is displayed on even columns. Both left and right images are displayed simultaneously. The LCD system also has an external control line for setting of the left/right image ordering on the pixel columns. This is required for the electro-optical system to achieve adequate zone overlap between the three possible zone settings.

2.3 Head Tracking System

As described, the LCD and dynamic parallax illumination subsystems function together to create a controllable stereo viewing zone positioning system. In order to maintain a correct stereo image to a viewer, these subsystems must be set to appropriate states based on the viewer's head position. Viewer head position coordinates are obtained from a sensor subsystem which tracks a viewer's head and processes position coordinates to calculate which of the discrete display zone states must be set to achieve a correct stereo image. The appropriate display control signals are then issued to the LCD and parallax illumination subsystems.

2.4 Image Generation System

The computer system used for generation of stereo graphics was a Silicon Graphics Personal Iris workstation. Application software was adapted which generates left/right stereo image pairs. The workstation interfaces to the display system via an RGB video connection.

3. SYSTEM SPECIFICATIONS

The display system developed under this program met or exceeded almost all of the original contract specifications.

Table 2
Final Display System Specifications

Requirement	Contract	Actual
Viewing Area	161 sq. cm.	310 sq. cm.
Color	8 colors	4096 colors
Luminance	171 cd/m^2 min 514 cd/m^2 goal	356 cd/m^2 3D 291 cd/m^2 2D
Contrast Ratio @100 fc @10,000 fc	 20:1 4:1	 40:1 25:1
Non-uniformity 2D 3D	 <30% <30%	 39% 29%
Dimmability	250:1 min 1000:1 goal	153:1 3D 56:1 2D
Power Consumption	<200W	166W
Features 2D/3D Head tracking	 YES YES	 YES YES
Interface	RS-170A video	RS-170A video
Packaging	2.54 cm border 15.24 cm depth	3.81 cm border 45.72 cm depth

In addition to these top level requirements, additional objectives were identified during the continued development of DTI display technology. Using the top level requirements, we developed a conceptual system design and defined specific subsystem requirements. Requirements were carefully allocated and reviewed for completeness. The resulting subsystem specifications are discussed below.

3.1 Dynamic Parallax Illumination System

During the program, two dynamic parallax illumination systems were implemented. First an electro-mechanical system was developed. Following this, an electro-optical system was designed which utilized much of the original electro-mechanical system components. Both systems are described below.

3.1.1 Electro-mechanical

3.1.1.1 Illumination

The critical requirements for the illumination system were sufficient luminance to provide at least 171 cd/m² (50 fL) after light goes through the LCD, and a high degree of uniformity. Since the LCD and optics may absorb up to 97% of the light impinging on them, this implied delivery of 5709 cd/m² (1667 fL) to the rear of the LCD and optics. However, since light is being focused into thin vertical lines, light loss due to opaque vertical pixel areas is reduced.

Finally, the light sources had to be in the form of long thin vertical emitters with a certain amount of dark unilluminated space between them, which implied that the luminance within the emitting areas would have to be much higher than the 5709 cd/m² (1667 fL) figure given above.

Other requirements included a 250:1 dimming range, a capacity to accommodate 2D as well as 3D viewing, a luminance and contrast unevenness of less than 30%, and an overall display power consumption requirement of less than 200W.

After examining several possible light sources, aperture fluorescent lamps were chosen because they were sufficiently bright, were efficient, were easy to work with, and were the illuminator of choice in nearly all LCD applications. This final illumination system consisted of the following two segments:

(1) **Lamps** - The illumination system that was initially built consisted of nine vertically oriented fluorescent aperture lamps. The lamps were specified to be 1.1 cm in diameter with .6 cm wide apertures to provide maximum 2 within the aperture. When the lamps were new, their luminance was measured to be 68,498 cd/m² (20,000 fL) within the apertures when driven to the point where further power input would produce diminishing returns. The luminance will slowly degrade over time, as with other fluorescent lamps, resulting in need for replacement after several thousand hours of operation.

(2) **Lamp Drivers** - The electro-mechanical system used a purchased high voltage supply combined with DTI electronics to drive the lamps with a 400 Hz signal. Dimming was accomplished by pulse width modulation.

3.1.1.2 Optics

The optics system must image light from the nine vertical light sources of pitch 1.017 cm, with 3.05 cm apertures, and a width of .6 cm, located 9.0 cm behind the lens into 648 narrow vertical light lines, with the precise pitch requirements described above, on a diffuser mounted behind the LCD. The following are pertinent specifications for each of the optical components:

(1) **Lenticular Lens** - The most critical specification for the optics are the pitch and focal length of the lenses. Light lines with a width of .008 cm ±.003 cm had to be generated behind the LCD pixel layer. For use with this LCD the required light line pitch was calculated to be .03188 cm, with a random position error of any line with regard to a reference edge line of no more than .00159 cm allowed. The light lines had to be parallel to the LCD pixel columns to within 10.7 arc seconds and overall lateral position errors of no more than ±.006 cm were tolerated. In

order to produce light lines with the required position accuracies, the required average pitch of the lenses was determined to be .03146 cm with an allowable random position error of .00159 cm, and a lens radius of .0436 cm ±.00436 cm. Given a lens pitch and focal length within tolerance, the light lines would have the required pitch and furthermore different lines resulting from different lamps would be superimposed on each other.

(2) **Diffuser** - The diffuser specifications were not as critical. Only a weak diffuser is needed. The diffuser had to be strong enough to wash out unwanted bright areas in regions that are illuminated by two lamps, yet weak enough that the reflected light off the diffuser does not contribute significantly to ghost image visibility.

(3) **Mounting/Alignment** - A lens mount was designed that attached directly to the LCD assembly and contained manually operated adjustment mechanisms using cams for position and rotational adjustments to the required accuracy.

(4) **2D/3D Diffuser** - Means had to be provided to allow the display to be used in 2D as well as 3D modes. For 2D mode, it was required that all pixels of the display be visible to both eyes so that conventional full resolution 2D images could be displayed. An LC layer was used whose state of transparency could be switched from almost completely transparent to diffuse by varying the amount of voltage across it. This was installed between the lamps and optics and placed in transparent mode for 3D viewing and diffuse mode for 2D viewing. In diffuse mode, the lamp light scattered by the LC layer provided more even, diffuse illumination which was not focused into light lines by the lenticular lens, and thus both the observer's eyes were able to see all pixels of the LCD.

To maximize luminance and prevent uneven illumination, the optics were specified to transmit 90% of the impinging light with variation in transmittance across the display of less than ±5% To minimize unwanted reflected and scattered light which can cause ghost images to be visible, the use of glass with an optical anti-reflective (AR) coating as substrates for the lens was investigated. An AR coating on the lens was not implemented under the program because there was sufficient uncertainty as to its manufacturability. Ongoing research at DTI will determine the feasibility and benefit of developing an AR coated lens.

3.1.1.3 Servo Assembly

The electro-mechanical assembly which laterally moves the lenticular lens array consists of the following components:

(1) **Mounting Assembly** - The mounting assembly consists of two frames. An inner frame is suspended in an outer frame with four stiff flexures, which maintains frame alignment and minimizes the effects of shock and vibration. The assembly allows for lateral movement of the inner frame of about ±.1 cm, without resulting in any rotational or vertical offsets.

(2) **Servo Motor** - A 12 VDC drive motor was used which provides pulse signals indicating motor revolution. This output was interfaced to the control electronics.

(3) **Lead Screw** - A lead screw was attached to the inner mounting frame. One revolution of the lead screw resulted in .05 cm of frame movement. The lead screw was geared to the servo motor such that approximately 150 motor revolutions were required per .1 cm of frame movement. The control electronics therefore calculated lens movement based on motor pulse count.

(4) **Home Switch** - A switch was mounted at one end of the outer frame assembly. When the inner frame was driven towards this end of the frame, the switch would make contact. The switch was interfaced to the control electronics which provided a reference home position from which accurate lens positioning could be done.

3.1.2 Electro-optical

3.1.2.1 Illumination

(1) **Lamps** - For this implementation, the nine 1.1 cm lamps were replaced by twenty-seven .7 cm lamps. These were grouped into three sets of nine, any one of which is on at a given time for 3D viewing, and all of which are on at reduced power for 2D viewing giving equal luminance in 2D and 3D modes of operation.

(2) **Lamp Drivers** - For this system commercially available lamp drivers which operate from 28 Vac and provide 50 kHz voltage to each lamp were chosen. Key specifications for the lamp drivers were:

Input Voltage: 28 Vac
Open Circuit Voltage: 400 Vrms
Output Current Limit: 170 mA
Efficiency: 80%
Frequency: 50 kHz

Dimming in this case was also accomplished by pulse width modulation.

3.1.2.2 Optics

The optical components for the electro-optical system were basically identical to the electro-mechanical implementation. The servo mechanisms were eliminated from the lens mounting frame, and the 2D/3D LC diffuser was eliminated. 2D viewing mode was accommodated simply by turning all the lamps on. This created three sets of closely spaced light lines and caused at least one light line to be visible behind each pixel column to each of the observer's eyes no matter what the observer's position. Once again, each of the eyes was able to see all the pixels.

3.2 LCD System

The LCD used for this project had to possess a viewing area of at least 161.29 square centimeters, produce at least 8 colors, possess a contrast ratio that allowed 20:1 image contrast in 100 fc ambient and 4:1 in 10,000 fc ambient. Non-uniformity had to be low, and compact enough to allow construction of a display that was no more than 15.24 cm deep and 5.08 cm wider and higher than the active area of the LCD.

At the time the contract started, there were no color LCDs on the market with the required specifications. Two LCD manufacturers, Optical Imaging Systems and Litton Systems of Canada, had produced ruggedized color TFT military grade LCDs that could meet the requirements, and felt that they could supply an LCD to DTI for this program.

After extensive discussions with these two manufacturers, OIS declined to bid, and a Litton LCD with the following properties was chosen:

3.2.1 Display Panel

Resolution:	640 rows by 480 columns
Active area:	20.32 cm by 15.24 cm
Pixel Arrangement:	alternating quad pattern (see Figure 7)
Color:	4,096 colors and 16 gray levels
Transmittance:	3% minimum
Contrast ratio:	100:1

The color sub-element arrangement turned out to be of particular importance. If a normal quad pattern were used, the left eye would see only red and green colors in 3D mode, and the right eye would see only green and blue, since only alternate columns of elements would be visible to each eye. For that reason the alternating pattern shown in Figure 7 was specified. In 3D mode, each group of four color elements in a column was used as a pixel. In 2D mode, each square group of four was used as a pixel, as is usually done. This resulted in resolution of 640 x 240 in 3D mode, and 640 x 480 in 2D mode.

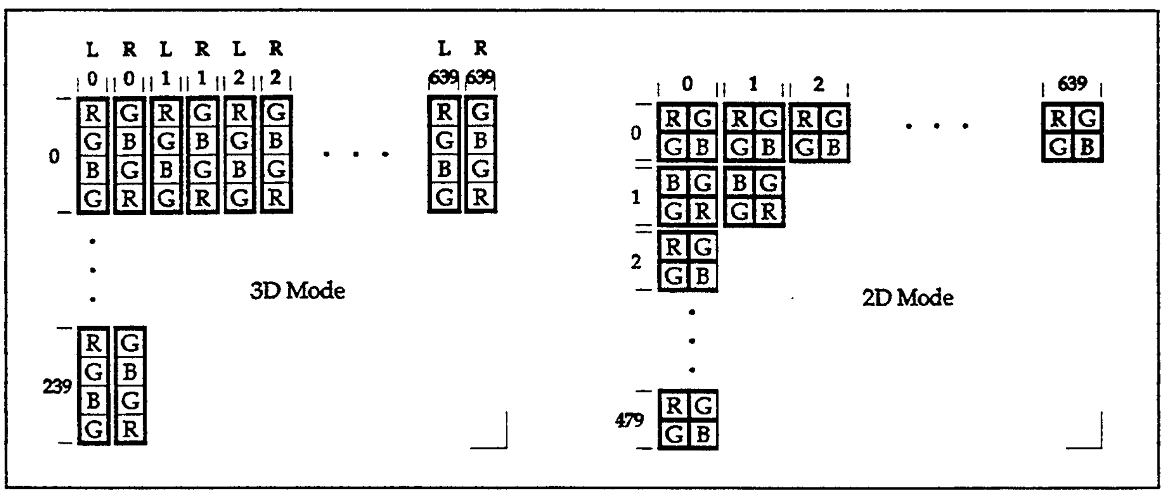

Figure 7
Cockpit Prototype LCD Pixel Structure

3.2.2 Interface

Display interface is via three separate video connections. One each for Red, Green, and Blue components of the image. The timing format for the signals is RS-170A video. The three channels must be synchronized together with video sync signals being provided on the Green component channel. This format can deliver to the display system, images of 640 (W) by 480 (H) pixels. Each pixel can be resolved into one of 4096 possible colors, or 16 possible shades per color component (R,G or B).

The required structure for left/right stereo images is shown in Figure 8. The left image is contained in the top portion of the full video image. The right in the bottom portion. Each image must be generated with a 2:1 width to height aspect ratio. The system processes these images and displays them on the LCD with the left image on odd columns and the right image on even columns. With the electro-optical system, the left/right image to pixel column ordering is controlled by the head tracking system.

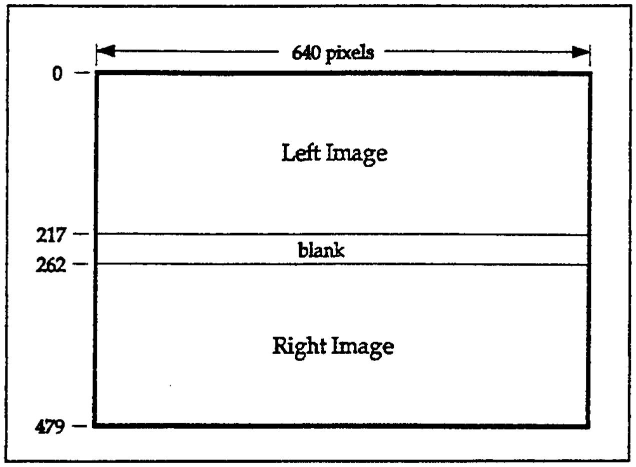

Figure 8
Cockpit Prototype Stereo Image Structure

3.3 Head Tracking System

The head tracking system provides information on the head position of a viewer. This information is processed by a microcontroller to set the parallax illumination system. Critical requirements included: sensor accuracy, which needed to be fine enough to maintain a proper zone for the viewer; and system responsiveness, which needed to be fast enough to avoid loss of stereo and other visual artifacts during head movement.

3.3.1 Head Position Sensor

Throughout the program a Polhemus Isotrak magnetic sensor device was used. This technology was chosen because of its use in cockpit applications. It consists of a sensor device which is tethered to the user and thus does not offer the possibility for completely unobtrusive operation. It also is subject to distortions within the magnetic field. It has the following key specifications:

Sampling:	X,Y,Z
Range:	±61 cm in X,Y,Z
User Interface:	Tethered magnetic sensor device
Resolution:	±.152 cm in X,Y,Z
Sample Rate:	58 Hz
Latency:	25 ms (unfiltered)
Data Rate:	19.2K baud (max)

3.3.2 Head Tracker Control

Two different microcontroller systems were used during the program. Initially, an 80186 based device was used to control the servo motor in the electro-mechanical system. Due to poor programming tools available for this board, we chose an alternate board for the electro-optical implementation. This board has the following key specifications:

Processor:	80C88, 10 MHz
Size:	8.9 cm x 12.7 cm
Power:	5 V at 380 mA
Interface:	2 serial ports @ up to 30.4K baud
	32 TTL lines

Firmware development to process data from the Polhemus system and control the illumination system was developed using C language. Serial communications with the Polhemus system were set at 19.2K baud.

3.4 Image Generation System

3.4.1 Graphics Workstation

Throughout the program a Silicon Graphics Personal Iris Workstation was used. It has the following specifications:

Model:	4D 20G
Processor:	R2000 RISC, 12.5 MHz, 10 MIPS
Graphics:	24 bit color, 5K polygons/sec
Video Interface:	RGB RS-170A timing

3.4.2 Software

Two software applications were adapted for use with the display system. First, a program called GLOBE, supplied by Wright Patterson was adapted. The program depicts an aircraft inside a sphere. The sphere is segmented into different sectors which are capable of changing color to signify the direction of approaching potential hazards. The program, which was already creating stereoscopic images, was modified to output left/right image pairs in the appropriate format and video timing.

The second application used was a program developed at NASA Langley Research Center (Hampton, VA). The program, Electronic Visual Flight Rules, is a flight simulation application which graphically depicts safe flight pathways and other flight data. This application was also capable of creating stereo pair images, and was adapted for use with the prototype display under the program. The program provides an impressive perception of depth.

4. SYSTEM TESTING AND VALIDATION

During the course of the program, several system and subsystem test procedures were developed and conducted. Final acceptance testing was performed on the electro-optical head tracking system which was delivered to WPAFB. The following is a summary of the procedures and results of this testing.

4.1 Test Procedures

A primary display acceptance test procedure was used to validate the high level system requirements which were contract commitments. In addition, for the development of the electro-optical tracking system, DTI implemented a more formal specification process. For each specification developed, a validation checklist was developed which identified a validation method for each requirement. Many requirements were validated through inspection or analysis. Those requiring testing for validation had corresponding test plans. A complete report of all system testing can be found in the Requirements Validation Report (Related Documentation, reference 1). Here is a summary of test procedures which were conducted:

(1) **Acceptance Test Plan** (ref. 2) - This test plan defined procedures to test each contract requirement.

(2) **LCD Acceptance Test Plan** (included in ref. 1) - This document was generated by Litton Systems for validation of the LCD system requirements as defined in the purchase order.

(3) **Tracking Control Test Procedure** (included in ref. 1) - This test plan was for performance analysis of the tracking control operation of the system. Test results collected with this procedure allowed for verification of system requirements pertaining to the tracking mode of operation of the display system.

4.2 Results

All the system requirements developed were validated through testing, inspection and/or analysis. Requirements not met were documented as requirement exceptions. Of the approximately three hundred requirements defined, there were thirty exceptions in all. Three requirement exceptions, relating to dimmability and illumination evenness, were in violation of contractual specifications. The following is a summary of all the requirement exceptions:

Six requirements proved to be untestable. These include reliability and component life requirements, where testing would be infeasible and manufacturer specifications were not available (e.g. lamp life specs).

Five requirement exceptions proved to have no noticeable impact on system performance. In these cases, the exception was either compensated for in system design, or the requirement defined was excessive.

Seven requirement exceptions were directly or indirectly related to performance of the Polhemus sensor system. The primary performance issue associated with the Polhemus is the tracking field distortions which can be introduced by metallic objects in the operational environment. Because the system environment is not static, field distortions can vary significantly. We have compensated for distortions introduced by other system components

(i.e. the LCD system), but have not implemented any compensation methods for distortions introduced by other objects within the environment. It is feasible to implement a firmware version for a given static environment, once such an environment is defined. Meanwhile, when configuring the system, avoid placing it near metallic objects or objects which generate magnetic fields, such as CRTs.

Four exceptions were related to visual performance of the display during viewer head movement. These exceptions were primarily the result of excessive system update latency times. System latency, the period between viewer head movement and display update, was identified as being a critical requirement at the beginning of the program. A best effort was made to design the system for minimal latency, however design constraints imposed by pre-defined system components (such as the Polhemus) prevented us from achieving the target latency time of 20 ms. For a more in-depth discussion of system timing performance see document #10102, "Head Tracking Performance Analysis" (included in ref. 1).

Two exceptions relate to the reliability of the optical alignment of the system. Controlled testing for reliability of system mechanicals was beyond the scope of the program, but we did perform analysis of optical alignment each time the system underwent shipment or extensive handling. Results of these analyses showed inadequate stability of optical alignment with normal handling. Therefore we were not able to validate related requirements. Since the time of testing, we have gained further experience with the optical mounting assembly. Design iterations performed during the development of the commercial prototype system have yielded a reliable mechanical mounting solution.

One exception relating to image ghosting or crosstalk was identified. Ghosting is a critical performance factor for stereo imaging and we have done much to address the issues associated with it. System performance is marginally short of the requirement specified. We have identified methods to further improve on ghosting performance which could be implemented in future development programs.

Two exceptions are associated with illumination dimmability. Dimmability performance is impacted by minimally two factors. One is the lamp drive electronics, which achieve luminance levels through pulse width modulation drive of the lamps. Discussions with the lamp driver vendor indicate that with modified drivers, the 250:1 requirement can be exceeded upwards to a 1000:1 range. In practice, it was found that lamp luminance increases with temperature. This effectively adds a constant to the dim and bright levels which decreases the dimmability ratio. (See Document #10096, "Test of Illumination Electronics and Lamps for Head Tracking", included in ref. 1).

One exception for luminance uniformity was identified. We noticed that variance in temperature across the lamp array results in non-uniform luminance across the screen. This non-uniformity is particularly evident at a dim luminance setting. At the lower luminance levels, slight variances in luminance become more apparent due to the increased sensitivity of the eye at the lower luminance levels. Non-uniform temperatures in the lamp array are primarily due to fans being present on only one side of the unit. Therefore the lamps are cooled non-uniformly. This can be addressed in future designs.

One exception for even illumination within the entire viewing volume was identified. This specification was defined as a goal in attempts to address issues associated with lamp to LCD spacing. The lamps of the illumination system essentially cover the active area of the LCD only. Because the lamps are located some distance behind the LCD, at viewing angles off of tee-on position, there will be visible areas at the edges without illumination. The result is a dark band along the edge at off-angle viewing positions. Providing illumination in these areas is possible through alternative illumination configurations.

One exception was noted for system maintenance. It was specified that no internal maintenance be required by the user. The lamps used in the illumination system have a limited life span, therefore internal access is required for lamp replacement. Existing system design did not allow for easy access to the lamp array. Documentation was developed describing a maintenance procedure for disassembling and replacing lamps.

4.3 Tracking Analysis

Following system acceptance testing, a timing performance analysis of the system was conducted. This analysis is useful for understanding the critical latency time of the system. Latency has a significant impact on visual performance. Slow response time introduces delays which will appear as visible artifacts when a viewer moves their head. The results of this analysis can be used for future design and investigation efforts to improve system performance.

The timing intervals for all the major subsystem processes were measured. This allowed us to determine the overall time interval required for the display system to form a complete stereo image after a viewer moves from one zone state to another.

Figure 9 shows the various processes and timings within the head tracking system. The timing of the head tracking system is driven by the LCD vertical sync signal, which is a 60 Hz signal. The Polhemus sensor is directly synchronized to the LCD, and thus is acquiring positions also at a 60 Hz rate. There is a 25 ms delay (as specified by Polhemus), between when sensor movement can occur and the Polhemus system has position data available for transmission. Transmission time over the RS-232 port operating at 19.2K baud is about 7 ms for a 13 byte data packet. This means the total time from head movement to when data is available for position processing is 39 ms.

Once data is received, time to compute zone setting information is an average of 5 ms. Communication of parity information (2 bytes) to the display takes approximately 2 ms at 9600 baud. Response of the illumination system is virtually instantaneous. Therefore, position processing and control is complete approximately 50 ms after head movement.

Because processing is synchronized with LCD scan, the LCD begins updating according to a new parity state immediately after zone parity is communicated. LCD scan takes roughly 14.5 ms and pixel response is on the average of 40 ms. Therefore a complete image for the viewer's head position is formed on every pixel of the LCD about 104 ms after the viewer head movement occurs.

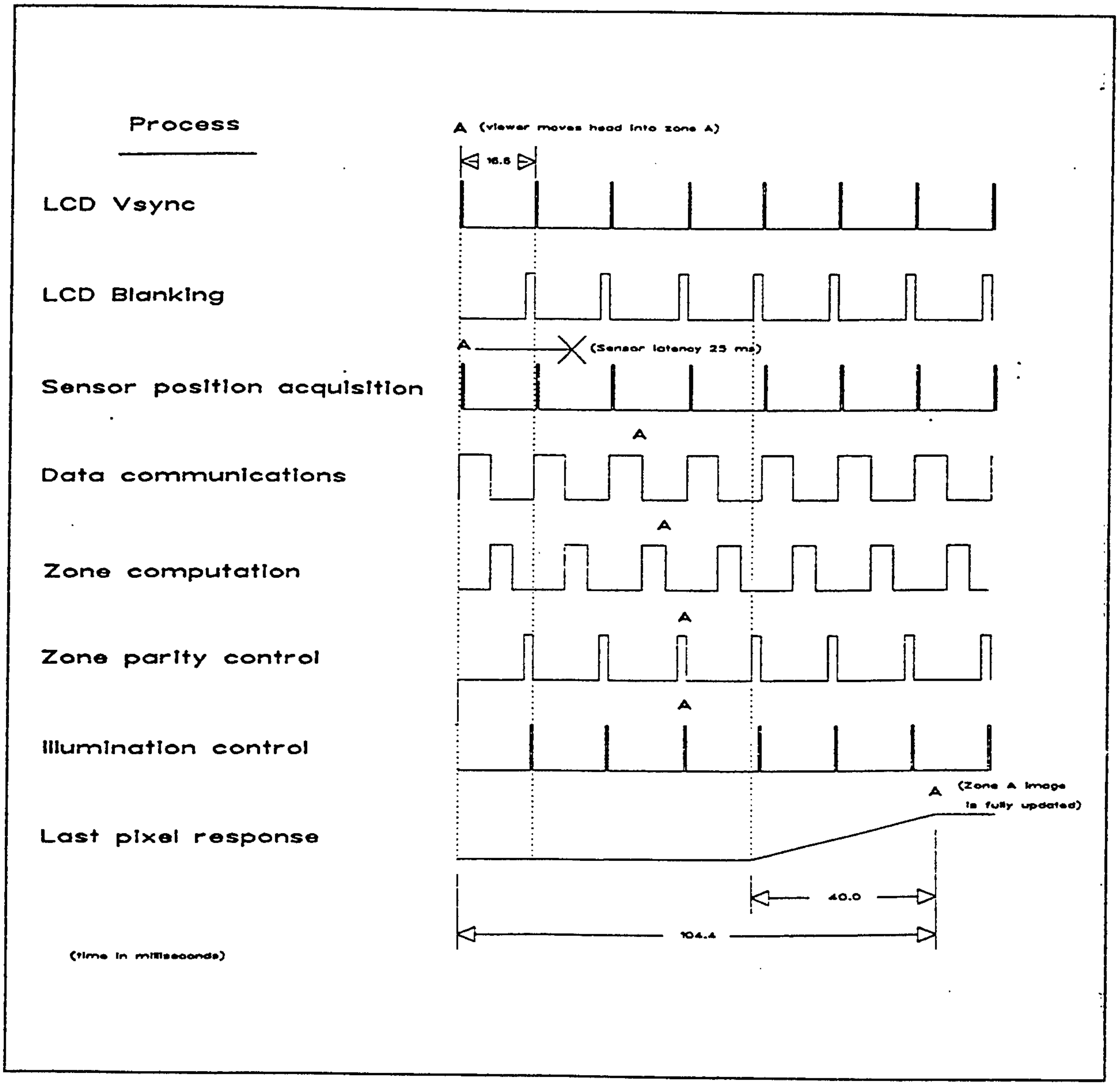

Figure 9
Head Tracking Display Update Timing

It is clear that the 104 ms update delay is well off the target specification of 20 ms. One would anticipate severe ghost images during head movement. This artifact is certainly evident in the system, although not as severe as expected. The ghosting is somewhat diminished due to the update and pixel response curve of the LCD. We have also reduced this artifact by actually delaying the update of the illumination system one update cycle. By doing this, the time variance between illumination update and LCD update is decreased by 16.6 ms. In the current system, switching pixel states accounts for roughly ½ of the image update time. Eliminating the requirement of having to change left/right pixel ordering on the LCD would significantly reduce the ghosting artifact introduced by head movement. Pixel switching can be eliminated with alternate illumination system designs. Future developments will certainly eliminate this requirement.

The second major contributor to system delay is the sensor latency time of 25 ms. This time would have to be under 10 ms in order to meet the system requirement of 20 ms. Sensor latencies are highly dependent on the sensor technology used. Latency is certainly a critical requirement when choosing or designing an appropriate sensor system. For latency information on alternate sensor devices, see the "Head Position Sensor Technology Evaluation" report, Doc. #10049, included in ref. 1.

Other processes such as data communication and processing times, can definitely be reduced with alternative processing hardware. In the future, processing hardware could be integrated into sensor hardware which typically has existing internal processing devices. Meanwhile, the current implementation allows for easy integration and testing of sensor devices. The added latency is currently not a problem, and could easily be reduced or eliminated when a specific sensor device is identified for use in product.

5. DISPLAY COLLIMATION

It is believed, based on testing performed at NASA - Langley Research Center, that collimating a stereoscopic or autostereoscopic display will accrue benefits to the user including a greater useful imaging volume and more accurate stereo perception. DTI therefore investigated the feasibility of collimating an autostereoscopic display, and experimentally demonstrated a proof-of-concept model of such a display.

Studies conducted at NASA - Langley Research Center indicate that the volume of virtual space within which images can be represented on a stereoscopic display without the observer experiencing difficulty in focusing or fusing the images, or experiencing errors in perceived object distance, is limited.[1,2] It is believed that both these difficulties arise from a single cause: looking at an image on all stereoscopic and most autostereoscopic displays differs from looking at the real world in one important respect. When looking at the world, one nearly always focuses the eyes and converges them at the same point in space. When looking at a display, however, the eyes are always focused at the display surface, but may be converged at points far in front of or behind it. This atypical use of eye muscles is believed to be the major cause of the difficulties noted above and also the eyestrain and temporary disorientation experienced by many, particularly beginners, when using stereoscopic displays.

The studies performed at Langley have shown that the virtual volume within which observers can comfortably and accurately perceive stereoscopic images is dependent on the distance between the observer and the display surface. For screens tested at viewing distances of 48 cm - 145 cm, the distance objects could be represented in front of the screen was limited to about 25% of the screen to eye distance by test subjects' difficulty in focusing on images closer than that. The distance that objects could be represented behind the screen was limited by inaccuracies in depth perception that increased as the screen to object distance increased. These inaccuracies become significant (> 10%) at distances greater than 160% of the screen to eye distance. For example, on a display viewed at a typical distance of 76 cm, the usable volume extends 19 cm in front of and 122 cm behind the screen surface.

The Langley studies also found that the usable volume becomes very large if the display is collimated or nearly collimated. Although an exact determination of the close in limit has not been made, the usable volume extends from several feet in front of the observer to infinity. Thus a collimated display is most suitable for applications in which imagery occupying a large volume must be displayed.[2]

5.1 Collimating an Autostereoscopic Display

A collimated autostereoscopic should possess the same advantages noted above for a collimated stereoscopic display. It had been previously determined that DTI's parallax illumination technology can be used behind a collimated LCD. An LCD being used with DTI's parallax illumination system must be collimated in the usual manner, by a lens or mirror placed one focal length from it. The eyes will then focus at infinity when viewing the dual flat 2D images created by the LCD. DTI discovered that its parallax illumination system can be designed to take the presence of collimating lenses into account, thus creating viewing zones of the proper size at a comfortable viewing distance from the collimating optics.

The design of the optical and illumination elements depends on the pixel pitch of the LCD, the desired viewing distance, and other factors. In all cases, however, the illumination system is designed taking account of the fact that the size and position of the viewing zones created by it will be affected by the collimating optics in exactly the same way as any other object or image in the system. The final set of viewing zones will represent an image, formed by the collimating lens, of viewing zone "objects" created by the parallax illumination system and the display device. Furthermore, an observer's eye anywhere within one of the viewing zone images will see the same image on the display as the eye would see if it were located within the corresponding viewing zone object. Head tracking can be accomplished by moving the viewing zones, again taking the re-imaging action of the lens into account.

Thus, in order to create viewing zones of a certain width at a certain ideal viewing distance in front of the collimating lens, one must first, with the parallax illumination system, create the viewing zones in such a position that their images, formed by the lens, are of the required size and at the proper distance in front of the display.

Possible display, lens and observer position arrangements can be grouped into three categories: The distance between the observer and lens is less than one lens focal length, the distance between the observer and lens is equal to one focal length, and the distance between the observer and lens is greater than one focal length.

(1) Observer distance less than one focal length from the lens.

If the observer is to be seated at less than one focal length from the lens, the object viewing zones must be created at some location in front of the lens, at a distance greater than the ideal viewing distance, so that their images will be positioned with their laterally widest areas at the ideal viewing distance.

This can be accomplished by making the pitch of the light lines slightly narrower than the pitch required for direct viewing, but still greater than the pitch of the LCD pixels.

(2) Observer distance one focal length from the lens

A special case exists when the ideal viewing distance for the observer is one focal length from the lens. Then the object viewing zones must be created with their horizontally widest points at infinity, so that the widest areas are reimaged at one focal length from the lens.

This can be accomplished by making the pitch of the light lines equal to the pitch of the LCD pixels.

(3) Observer distance greater than one focal length from the lens

Under these conditions, the object viewing zones will have to be located behind the image display surface in order for their images to be located at the viewing distance. Viewing zones located behind the image display surface can be thought of as virtual images created by the image display surface and its optics.

This can be accomplished by making the pitch of the light lines slightly less than the pitch of the pixels.

5.2 Collimation of the Cockpit Display

Compact collimated versions of the cockpit display using a simple Fresnel lens were investigated. It was felt that a 45 cm fl Fresnel lens of 45 cm width could provide a reasonably distortion-free image across several inches of viewing space in the horizontal and vertical directions.

The parallax illumination system within the autostereoscopic cockpit display built under this program could most easily be reconfigured for collimation by redesigning and slightly repositioning the lenticular lens, and keeping all other illumination components identical. The lens pitch would have to be changed slightly to .03147 cm to produce light lines that have the same pitch as the LCD pixels. The change in radius required would be so small that it could be ignored. The lens would be mounted closer to the LCD pixel layer, so that the light lines form at a distance of .0115 cm from it. Under these conditions it was calculated that 6.3 cm wide viewing zones would be produced 45 cm in front of the lens.

Various folding mirror arrangements were investigated to determine whether compact collimated display could be built. A roughly 50 cm (wide) x 70 cm (high) x 45 cm (deep) model could be built given the 45 cm focal length Fresnel lens, and provided that a 75% sacrifice in luminance due to a partially reflective mirror could be tolerated. Such light loss would be unacceptable for an aircraft display, but might be acceptable in a model intended for human factors testing.

Building a collimated version of the autostereoscopic cockpit display was beyond the scope of this program. A bench model was built, however, under a different program using a black and white VGA LCD with illumination behind it that provided a light line pitch equal to the pixel pitch. The widest areas of the viewing zones were thus at infinity. A 32 cm diameter, 39 cm focal length Fresnel lens was then mounted 39 cm in front of the display. The viewing zones were successfully imaged to the correct size at a distance of 39 cm from the lens. Observers could easily see the autostereoscopic images. Due to the simple off-the-shelf Fresnel lens used, distortion became apparent when the display was viewed from more than a several centimeters off axis. A future prototype system will use a multiple lens design to achieve distortion free viewing over a wider area.

In addition to increasing the usable image volume and making the images easier to focus on and fuse, a collimating system magnifies the display, making today's rather small LCDs appear to be as large as high end CRTs. This latter effect creates a wide angle image that seems to create an immersive effect similar to that experienced by wearers of virtual reality headgear.

5.3 Design Issues and Challenges

The design issues and challenges that are associated with the development of a collimated 2D display are also associated with development of a collimated autostereoscopic display. They include:

<u>Wide viewing angle requirements</u>
It is often desirable to be able to view a display from across a wide viewing angle. Viewing a collimated display is similar to viewing a distant scene through a window that is the same size and shape as the collimating lens. In order for any particular part of the scene to be visible from any point across

a wide viewing volume requires a large collimating lens and deep display system.

Accommodation for cross-cockpit viewing
In an aircraft, the need for a wide viewing angle can arise from a requirement that two persons be able to view a display from two sides of a cockpit. In this situation, two discreet and mutually independent viewing volumes exist on either side of the cockpit. This might simplify the problem of accommodating wide angle viewing. For example it may be possible to make the display visible to both observers through a smaller lens by such means as a prism array or a half silvered mirror. In either case, autostereoscopic viewing can be provided.

Distortion Correction
A simple lens of short focal ratio will typically create appreciable distortion to the image, particularly when viewed from off axis. A dual or multiple lens or mirror system (such as the Schmidt systems commonly used) could be used to minimize distortion.

Minimization of display depth
Ideally, one would want a collimated display that is as thin as the non collimated displays used on portable computers. This is probably impossible because of basic optical considerations, but thicknesses on the order of the diagonal measurement of the display device could be achieved with short focal length collimating optics in combination with folding mirrors.

These issues could be addressed in a future program designed to create a practical collimated autostereoscopic display for cockpit applications.

References

1. Williams, Steven P. and Parrish, Russell V.: "Benefits, Limitations, and Guidelines for Application of Stereo 3-D Display Technology to the Cockpit Environment" Paper presented at the AGARD, Advanced Aircraft Interfaces: The Machine Side of the Man Machine Interface Conference, Session IV, Helmet Mounted Displays, Paper No. 12, Madrid, Spain, 1992.

2. Parrish, R.V., and Williams, S.P.: Determination of Depth-Viewing Volumes for Stereo Three-Dimensional Graphic Displays. NASA TP-2999, AVSCOM TM-90-B-016, 1990.

6. COMPACT DISPLAY DEVELOPMENT

In conjunction with the development of the electro-optical head tracking cockpit display system, a commercial prototype system was developed. Following the theme of "dual use" technology, the designs developed for the cockpit prototype system served as the basis for the commercial system. Using these designs, a prototype was quickly designed and implemented using off-the-shelf components. This effort was also minimized through use of existing designs of a DTI commercial display without head tracking. The end result of this effort is a very bright, reliable system, rich in interface capabilities. The system has proven very effective for demonstrating DTI technology in target commercial markets.

The commercial display has properties similar to the cockpit display. The challenge was to retain or improve on these properties and add a head tracking capability.

Table 3
Commercial Prototype Display Specifications

Property	Specification
Viewing Area	310 square centimeters minimum
Color	262,000 colors
Luminance	325 cd/m² (95 fL)
Contrast Ratio	100:1 min in 100 fc ambient
Non-uniformity	Luminance and contrast non-uniformity less than 30%
Power Consumption	160W
Features	Switchable 2D and 3D display modes.
Interface	Accepts input from IBM PCs, Apple Macintosh computers, video cameras, VCRs some workstations.
Packaging	36 cm (W) by 34 cm (h) by 17 cm (D)
Weight	13 kg

6.1 Dynamic Parallax Illumination

The existing illumination system for the commercial display consisted of eight 11mm diameter fluorescent aperture lamps and a lenticular lens designed to focus light from the lamp into precisely spaced light lines on a diffuser behind the LCD. Incorporation of head tracking involved replacing these lamps with three sets of thinner lamps that could be turned on and off according to input from a head position sensor.

6.1.1 Illumination

When electro-optical head tracking development began, the eight 11mm lamps were replaced by twenty-four .7 cm lamps, which were operated in the same fashion as in the cockpit display. They were grouped into three sets, any one of which is on at a given time for 3D viewing, and all of which are on at reduced power for 2D viewing giving equal luminance in 2D and 3D modes of operation.

For this system commercially available lamp drivers which operate from 28 Vac and provide 50 kHz voltage to each lamp were chosen. Key specifications for the lamp drivers were:

Input Voltage:	28 Vac
Open Circuit Voltage:	600 Vrms
Output Current Limit:	100 mA
Efficiency:	80%
Frequency:	50 kHz

6.1.2 Optics

The optics system was designed to image light from the eight (and later twenty-four) vertical light sources into 648 narrow vertical light lines, with precise pitch requirements, on a diffuser mounted behind the LCD.

The most critical specifications for the optics were again the pitch and focal length of the lenses. The required accuracies were even more stringent than in the cockpit display. Because the LCD used has a vertical stripe pixel arrangement (see LCD section below), the number of horizontal color elements per pixel was three versus the one horizontal element per pixel for the cockpit system's LCD. Therefore, light lines with widths of .005 cm ±.002 cm had to be created. The specified light line pitch was .022038 cm with a random position error of any line with regard to a reference edge line of no more than ± .001 cm. The lines had to be focused in a plane parallel to the LCD at a distance of .13 cm from it. Rotational misalignment of no more than 7.4 arc minutes was specified. Lateral position accuracy had to be maintained to within ±.004 cm.

In order to produce light lines with the required position accuracies, the required average pitch of the lenses was .021882 cm with an allowable random position error of ±.0001 cm and a lens radius of .0337 cm ±.003 cm. Given a lens pitch and focal length within tolerance, the light lines would have the required pitch and furthermore different lines resulting from different lamps within the same set would be superimposed on each other.

The diffuser specifications again were not as critical. Only a weak diffuser is needed, it had to be strong enough to wash out unwanted bright areas in regions that are illuminated by two lamps, yet weak enough that the reflected light off the diffuser does not contribute significantly to ghost image visibility. For this display a diffuser was used which is identical to the one ultimately used in the cockpit display. It consists of a polymer layer deposited on glass.

An improved lens mount was also designed under this program that was attached directly to the LCD assembly and contained manually operated cam adjustments for position and rotational adjustments to the required accuracy. This design overcame some of the stability issues experienced with the cockpit prototype implementation.

6.2 LCD

An off-the-shelf LCD, manufactured by Sharp, was used for the commercial prototype system. It possessed the following properties:

Resolution:	640 rows by 480 columns
Active Area:	20.32 cm by 15.24 cm
Pixel Arrangement:	RGB stripe
Transmittance:	approx. 3%
Contrast Ratio:	100:1

Use of a control board designed for an overhead projector LCD allowed generation of 262,000 colors. The controller also provides video interface capability to NTSC, SVHS, RS-170A RGB, VGA, and Macintosh.

The color stripe arrangement required that interleaved sets of red, green, and blue element columns be used as pixels in 3D mode, since odd columns or elements had to be used for left eye images and even columns had to be used as right eye images. In 2D mode, groups of three adjacent red, green, and blue elements were used as pixels in the usual manner. Thus resolution is 320 by 480 in 3D mode, and 640 by 480 in 2D mode (see Figure 10).

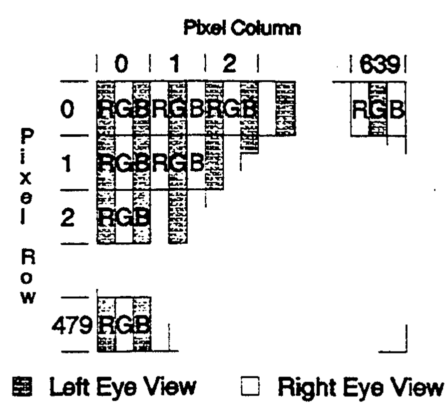

Figure 10
Commercial Prototype LCD Pixel Structure

6.3 Head Tracking

For the commercial system a Dynasight sensor device made by Origin Instruments was used. The system tracks a viewer using emitted infrared (IR) which reflects off a small dot. The viewer must wear a passive IR reflecting dot (.7 cm in diameter). The system has very good performance properties, as listed below:

Sampling:	X,Y,Z
Range:	±41 cm in X,Y,Z (w/.7 cm target)
User Interface:	near IR tracking of passive dot worn by user
Resolution:	±0.01 cm in X,Y,Z
Sample Rate:	33 Hz max
Latency:	16 ms min

This system also utilizes an RS-232 interface for data communications. It was interfaced to a microcontroller identical to that used in the cockpit prototype system. Firmware was developed which translated head position coordinates into the appropriate illumination state.

7. FUTURE DEVELOPMENT

As proven under this program, the concept of dynamic parallax illumination is functionally sound. However, further development is required to implement a practical embodiment with the needed performance. While the efforts of this program have yielded an impressive demonstration of high quality autostereoscopy, there remains much room for improvement and further understanding. There still remain many complex issues relating to reliability and performance. The program focus was largely upon functional aspects of achieving head tracking autostereoscopy. Efforts in the areas of performance have yielded a greater understanding of system requirements, but have also uncovered many issues which must be addressed by further engineering efforts. Additionally, as we move into these areas, the requirements for commercial and military implementations begin to diverge. Overall, DTI foresees many key areas in need of further research and development in order to realize the full potential of its head tracking autostereoscopic technology. These are:

(1) **Improved illumination array technology.**

The systems developed under this program use in excess of 20 fluorescent lamps for illumination. While the systems perform very well, questions of reliability, power efficiency and system size quickly come to mind. Critical in terms of commercial application is cost. The electro-optical method of dynamic parallax illumination requires multiple sets of vertical illumination segments. Increasing the number of segments will yield reduction in display depth and improvement in system visual performance. Unfortunately, increasing the number of segments is not feasible using the simple fluorescent lamp bank approach chosen under this program. Alternate approaches which offer the promise of improvement include:

(a) **Flat fluorescent lamps** - DTI has had discussions with a manufacturer of flat fluorescent lamps which can be used for LCD backlighting. Indications are positive for the feasibility of developing a flat lamp which would have multiple, controllable channels of illumination. This could yield a single, reliable component which would provide a large number of illumination segments. Given its early concept stage, there is a high risk level in terms of feasibility and manufacturability.

(b) **LC shutter arrays** - Under another program, DTI had developed an LC shutter array which worked in front of a simple fluorescent lamp bank. The shutter consisted of an array of controllable segments which could be set to an opaque or clear state. This allowed for a large number of controllable illumination segments. While functionally sound, this approach has drawbacks. One, the LC shutters decrease luminance by roughly 75 to 85% . Two, shutter contrast is relatively low which causes light leakage in the opaque state, and as a result, left/right image crosstalk. This approach holds promise, in terms of reliability and cost. Additionally, developments in LC shutter technology suggest improvements in shutter transmittance and contrast ratio are highly feasible.

(2) **High performance electro-mechanical methods for parallax adjustment.**

The efforts under this program on electro-mechanical means for creating dynamic parallax illumination, focused primarily on functional feasibility. In addition, concerns over the suitability of mechanical assemblies for military application led us to focus more heavily on electro-optical methods. However, we feel that electro-mechanical means still hold promise, especially for commercial application. Therefore, further investigation and analysis of electro-mechanical approaches is warranted. The primary thrust of such an effort would be in the areas of performance and reliability.

(3) **Improved LCD technology.**

The results of this program clearly demonstrate that there are no technical barriers in applying DTI technology to conventional LCDs. There is however, always a need for improvement in terms of panel size, resolution, color performance, viewing angle, and efficiency of light transmittance. Fortunately, these are properties which LCD manufacturers are committed to improving upon. DTI's task is to monitor this industry and carefully evaluate new developments.

(4) **Unobtrusive head tracking technology.**

An important and yet unfulfilled requirement for DTI's commercial display products, is completely unobtrusive viewer head tracking. This means nothing is required to be worn by the viewer to determine head position. Technology evaluations performed by DTI indicate that there are promising possibilities. Efforts towards this end could be undertaken through 3rd party development efforts, or through internal DTI development.

(5) **Improved system response to head movement.**

The update of the dynamic parallax illumination system is a critical factor in the overall visual performance of the display. As discussed, long latency periods between head movement and display update can cause annoying flicker and loss of stereo. Several system components contribute to this lag time. Sensor system latency is perhaps the most critical, and would have to receive careful consideration in any program to develop an unobtrusive sensor. Latencies due to computational times associated with illumination control could be minimized with faster hardware. Latency due to pixel response in the electro-optical system, could be eliminated with controllable illumination arrays having a larger number of controllable sets.

(6) **Advanced display interface electronics.**

For both display systems, the interface electronics were not developed by DTI. To achieve acceptable manufacturing cost levels, DTI must design and build its own LCD interface and control electronics. Additionally, in-house expertise in this area will allow for DTI to better respond to changing customer requirements and LCD technologies.

(7) **System reliability analysis and engineering.**

System reliability is a critical issue as DTI moves out of the research and development phase. Critical optical alignment requirements and

illumination component life are areas in need of careful analysis. DTI's experience under this program has brought many issues to the surface, which we will continue to addressed through rigorous analysis and design.

(8) **Manufacturing engineering.**

To successfully transition the technology from prototype to product, DTI must consider manufacturing issues. Again, from a product reliability standpoint, controlled and accurate assembly is critical. Material and labor associated with volume manufacturing must also be considered.

(9) **Human factors testing.**

For acceptance in military applications, human factors testing of autostereoscopic display systems will likely be required. Efforts to identify and quantify improvements in image perception and understanding using stereoscopic imaging have been performed previously. It is likely additional testing will be required to fully understand the impact of autostereoscopic viewing on human perception.

(10) **Development and deployment cycles for military systems.**

The path to deployment of DTI systems in the cockpit and battlefield is currently unclear. Development of systems to military specifications, and rigorous testing of the systems are areas DTI has yet to explore. DTI has begun working with several defense contractors to develop a clearer understanding of the necessary steps associated with military development and deployment cycles.

8. CONCLUSIONS - 3D FLAT PANEL COLOR DISPLAY

The results of this program demonstrate the feasibility of an autostereoscopic display with performance suitable for both military and commercial applications. In support of this claim, the following statements can be made:

(1) **Acceptable performance can be achieved with proven and available component technologies.**

The primary questions answered during the course of this program related to the viability of component technologies required in the proposed display system. Many issues were addressed relating to these key component areas:

(a) **LCD** - At the program onset, suitable color LCD systems were not available. Issues relating to pixel structure and system interface were addressed. Close cooperation with an LCD manufacturer yielded a rugged, military grade LCD system capable of real-time video interface and display. Further efforts in implementing the commercial prototype display system successfully utilized an off-the-shelf LCD. There is now no question of compatibility between conventional LCDs and DTI technology.

(b) **Illumination** - A major area of activity during the program was identification of suitable illumination sources. Display luminance, power and space requirements resulted in stringent illumination system requirements. Additionally, the electro-optical dynamic parallax illumination concept introduced requirements associated with creating a multiple set illumination array which could be switched at high speeds. After exploring many potential sources, fluorescent lighting was chosen. The work performed during the course of the program has proven that fluorescent technology can provide compact, very bright illumination. In addition, it has been demonstrated that high speed switching of fluorescent lamps is possible, and provides a highly efficient means for electro-optical dynamic parallax illumination.

(c) **Head tracking** - The ability to track a viewer's head position and adjust the illumination system appropriately was not considered a major challenge at the beginning of the program. The existence of proven tracking devices such as the Polhemus, provided a high confidence level for meeting this need. Efforts in this area soon revealed critical issues. While functional requirements were met with the development of the electro-mechanical system, this experience made us aware of critical performance requirements. During the electro-optical system development, a special focus was placed on head tracking performance. While the resulting prototype systems fell short of our performance objectives, a clear understanding of the requirements has been gained. In addition, a high level of confidence has been established in the feasibility of achieving accurate, responsive and unobtrusive head tracking.

(2) **Reliability and performance levels required for military application can be met.**

The cockpit prototype system developed makes use of component technologies which are already employed in military systems. The LCD system is a customized version of a display currently being used in military airplanes and helicopters. Fluorescent lamps are used in military LCD backlights. The optics and mounting assemblies in the display are simple, rugged components, no more fragile than the LCD itself. The magnetic head tracking device is currently the chosen device for military tracking applications. While developing a display system which meets military specifications is certainly a formidable task, the existing prototype convincingly demonstrates the feasibility of such a system.

(3) **Autostereoscopic displays with head tracking are commercially feasible.**

For DTI, an important part of this program was the implementation of a commercial prototype display system. This effort successfully coupled the cockpit prototype efforts with DTI's product development efforts. The result has been a quick and effective application of defense oriented research for commercial purpose. The commercial prototype system has provided the foundation for DTI's current product development. DTI is now selling small quantities of prototype displays for evaluation purposes in commercial and industrial applications. This is setting the stage for the development of a high performance, low cost autostereoscopic display system which can be applied in a variety of commercial markets.

The advancements made at DTI under this program have been significant. The experience gained by these efforts has provided practical knowledge which will be critical in the further development of an autostereoscopic display suitable for military and commercial application. The systems developed provide the necessary means to demonstrate the utility and effectiveness of stereoscopic display; a display method which has been limited in commercial application, and dismissed in cockpit applications due to the lack of suitable, unrestrictive viewing devices.

This program has successfully taken DTI through the proof-of-concept phase. The challenges ahead are to one, develop and refine a commercial product; and two, identify and begin the steps required to validate and deploy the technology for cockpit and other military applications.

SECTION B - A FIELD-SEQUENTIAL COLOR TECHNIQUE FOR LCDs WHICH DOES NOT EXHIBIT COLOR BREAKUP

9. INTRODUCTION

As previously reported, DTI successfully developed a flat panel color display under this contract which provides the user easy to see full color autostereoscopic 3D images and freedom of head movement without loss of stereo effect. These technological advances will significantly improve the utility of flat panel displays in avionic applications. However, a concern of the Air Force with regard to flat panels is their readability in bright sunlight. The Air Force has established specific luminance goals for LC displays in excess of 685 cd/m^2 (200 fL) with a power efficiency of .16 watt per square centimeter (1 watt per square inch) on an 20.3 cm x 20.3 cm (8" x 8") display with specular reflections to be about 1% to avoid visibility problems in high ambient illumination.

High quality full color LCDs use three to four independently controlled color elements for each pixel: one red, one green, and one blue, plus an additional green in the case of the four element quad configuration. The colors are created by the use of color filters which are located at the liquid crystal layer of the LCD. The disadvantages with these products are their high cost, limited resolution, and very low (3% - 4%) transmission of light, requiring a very bright, high power backlighter to achieve acceptable luminance. The high cost results in part from the extra steps required to deposit the color filters, and the comparatively low yields encountered when manufacturing LCDs with three times as many pixels as black and white models with equivalent resolution. The color filters also tend to increase reflectance, which boosts the display luminance requirement for high ambient light conditions.

As a result, present day LCDs do not meet the performance goals set by the Air Force. Various technologies are being developed by U.S. researchers and others to cope with this problem. One technology receiving considerable attention has been FSC illumination, which produces color images by sequentially illuminating a fast 180 fps monochrome LCD with red, green, and blue light. Before each color is flashed, the LCD is addressed and made to display the red, green, or blue component of the image, yielding one complete color image every 1/60th second. Since the eye cannot detect image changes at this speed, the observer perceives a nearly flickerless full-color image.

Use of such a technique could avoid many of the difficulties associated with the manufacture of high resolution LCDs by using fewer pixels; each rapidly changing pixel on the LCD does the work of a group of three red, green, and blue elements on a conventional color LCD. Furthermore, due to the lack of light absorbing color filters such displays could, in theory, achieve greater luminance than conventional LCDs. Lack of color filters also helps reduce specular reflection.

The generation of color images through FSC illumination, along with apparatus used to perform this function, is undergoing investigation at several locations around the world.

Previous conventional FSC devices have been unusable for avionics applications because of a phenomena called color breakup. If the user rapidly shifts his or her gaze, or is using a display in an environment where vibrations occur, the red, green, and blue image components tend to be focused on different areas of the retina. This results in an image that becomes broken up into

rapidly shifting red, green, and blue components, particularly around the edges. This can make the information on the display unrecognizable. As a result of this phenomena, conventional FSC illumination systems have not been accepted in many potential application areas.

Because of the great speed at which eye movement (saccade) and user vibrations can occur, experts have speculated that a field rate of 2,000 fps may be necessary to overcome color breakup problems. Such LCDs are well beyond the leading edge of the technology.

DTI devised an FSC illumination technique that is an outgrowth of its advanced autostereoscopic technology. DTI, with the endorsement of several vision experts, believed that this technique would eliminate color breakup phenomena and lessen the LCD speed required for flicker-free imaging, while retaining the other advantages associated with the FSC technique.

9.1 The DTI field-sequential color illumination system

DTI's FSC technique presents significant improvements over conventional methods by incorporating color distribution patterns and sequential interlaced line illumination patterns similar to those seen on an interlaced CRT. DTI's system works by focusing the red, green, and blue light into sequentially illuminated spots or lines within the pixel boundaries. Instead of simultaneously illuminating all pixels with the same color, the DTI configuration distributes all three colors among different pixels at any given time in such a way that all three colors have been imaged within each pixel after three frames have been presented. It was theorized that the particular way in which this was done would reduce or eliminate color breakup. Secondly, the way in which these rows of color spots are spatially and temporally interlaced is visually analogous to the interlacing of scan lines on a CRT. The difference is that for full color, the interlace must be 3:1 instead of 2:1. It was theorized that this interlace scheme could reduce the critical flicker frequency of the system by a factor of two or more.

Figure 11 shows one of several interlace configurations that can be generated with DTI's type of optics. This configuration is closest to the typical CRT row interlace scheme and therefore good for illustrative purposes. The figure shows a magnified view of two representative columns of pixels on an LCD. During the first 1/90th second, the LCD is scanned and the pixels in columns 1, 4, 7, etc. are made to change their transparency to display part of the red component of an image. Pixels in columns 2, 5, 8, etc. are made to change their transparency to display part of the green component of the image, and rows 3, 6, 9, etc. are changed to display another row of the blue component of the image. At the end of the second 1/90th second interval, light is focused into a second row of spots, marked t2, in the middle of each pixel. During the last 1/90th second interval, the pixels once again change to display the remainder of the image, and strobed light would be focused into a new row of spots, marked t3, in the bottom third of each pixel. The visual effect produced would be similar to that seen on an interlaced color CRT, except that instead of two sets of interlaced horizontal rows appearing sequentially, three rows would be used.

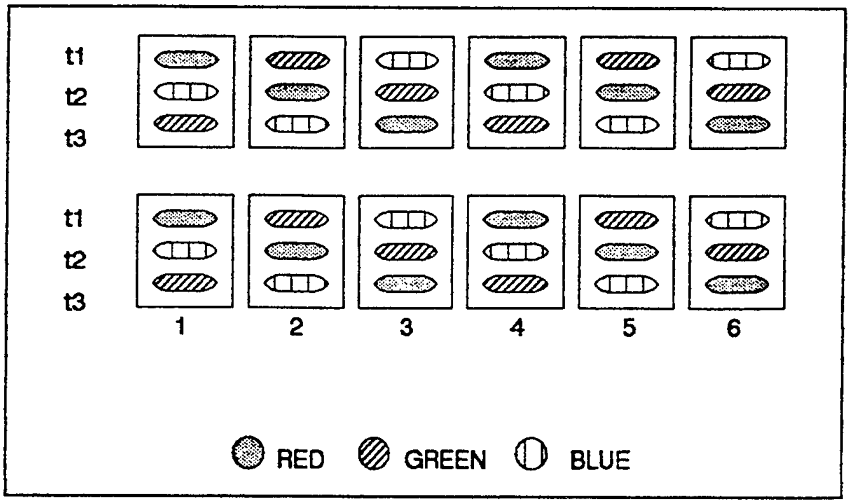

Figure 11
Field-Sequential-Color Illumination Pattern

Figure 12 shows an optical configuration that can be used in this type of system to generate the light spots and focus them onto the LC pixel layer. The illumination is provided by multiple sets of strobed lamps, each set containing red, green, and blue members.

A fly's eye lens, composed of a raster of square lenses, with lenses of nearly the same pitch as that of the pixels is placed parallel to the lamps, between the lamps and the LCD. The lens is used to generate a lattice of spots and to direct the spot images to the appropriate rows of pixels.

The end result is the same as that achieved with conventional FSC: brighter full color images with a resolution equal to the number of addressable elements on the LCD, but without the objectionable color breakup, and using slower LCDs with drivers and physical properties closer to those found on standard off-the-shelf LCDs.

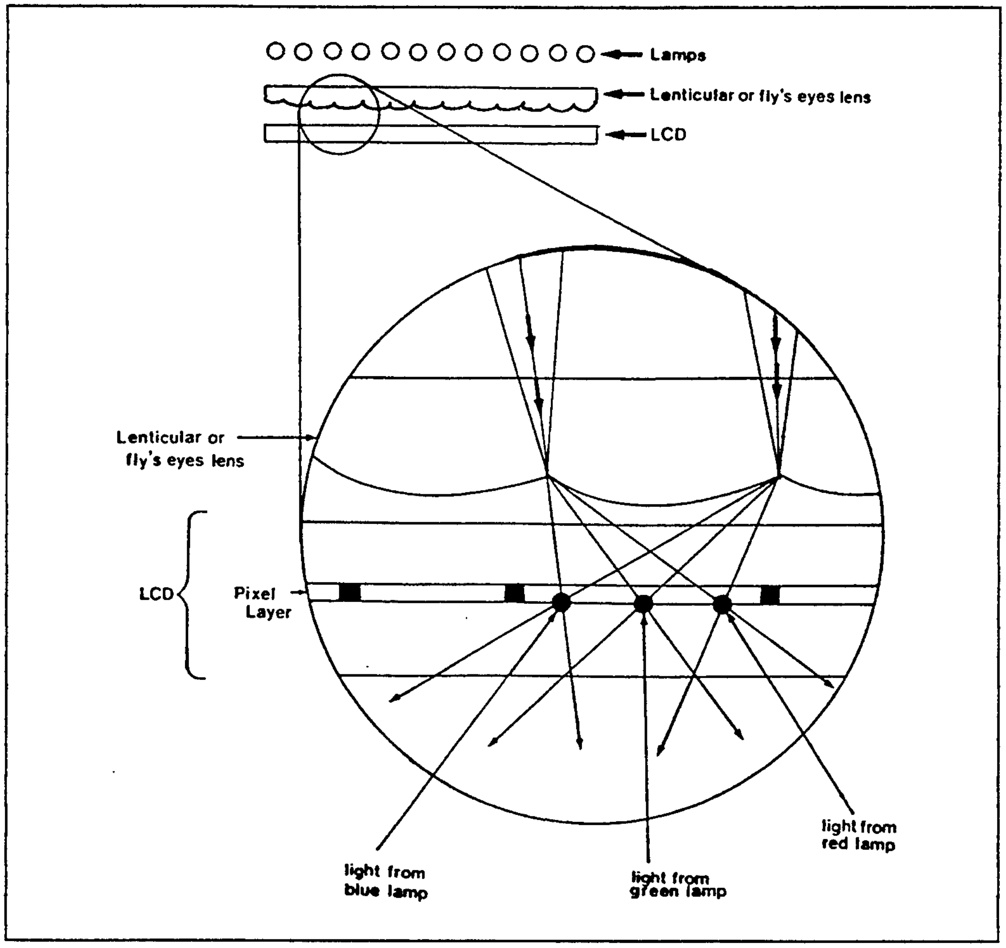

Figure 12
Creation of Field-Sequential-Color Illumination Patterns with a Fly's Eye Lens

9.2 Program Objectives

To demonstrate the concept in practice and to support claims of DTI's FSC illumination technique, the following objectives were established:

(1) Develop a breadboard model of a color AMLCD using DTI's Sub Pixel FSC Technology.

(2) Demonstrate improved performance over other FSC methods in the form of:

- Eliminated or Reduced Color Breakup
- Elimination of Flicker at Reduced LCD Frame Rates Through Interlacing

(3) Evaluate the effects of and capabilities to randomize the color patterns to further improve image quality.

(4) Gather baseline data on luminance, illumination evenness, LCD performance and image quality.

10. BREADBOARD DESIGN OVERVIEW AND REQUIREMENTS

Figure 13 diagrams the basic system architecture of the major subsystems making up an FSC display using the DTI technique. Each subsystem of the breadboard is described and the critical requirements are discussed in the following section.

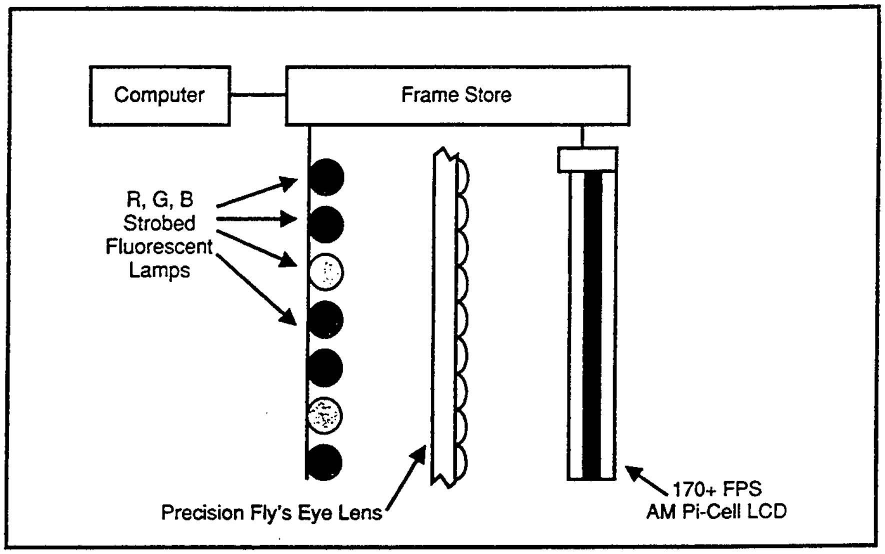

Figure 13
Breadboard System Major Components

10.1 FSC Illumination System

The purpose of the illumination subsystem is to generate patterns of RGB light to be imaged by the optics behind the LCD. This can be accomplished by means of sets of triads of RGB vertically-oriented linear light sources situated in a plane behind a fly's eye lens sheet, which focuses light from the light sources into a large number of light lines within the pixels of the LCD. Thus the FSC illumination system has two major subsystems: the illumination system (light sources, drivers and synchronization electronics) and the optics system (fly's eye lens). Each of these systems works in conjunction with the image generation to produce an FSC display.

10.1.1 Illumination System

Two alternatives for the breadboard illumination system were investigated. The first was steady white lamps combined with colored filters to meet chromaticity requirements and shutters to emulate flashing. The second was off-the-shelf or custom made flashing red, green, and blue phosphor fluorescent lamps.

Critical specifications for the illumination subsystem are chromaticity, speed, luminance and synchronization. Color coordinates that match existing avionics LCDs were defined as chromaticity goals. These differ from commercial LCD color coordinates due to the Air Force's need for night vision goggle compatibility and sunlight readability as defined in the Document

"Color, Flat Panel Liquid Crystal Displays For U.S. Military Aircraft, Working Draft 18 September 1992". The color coordinates are:

Red $u'=.400$, $v'=.522$

Blue $u'=.110$, $v'=.522$

Green $u'=.150$ $v'=.340$

Based on the speed of the LCD, the amount of time that the lamps could be on for is 4.0 ms. Therefore, the light sources should be capable of turning OFF to ON or vice versa in at most 4.0 ms, but preferably less to provide the maximum amount of time possible at peak luminance. In order to provide an Air Force required display luminance of 685 cd/m^2 (200 fL), it was initially speculated that the lamps would need to emit at least 188,370 cd/m^2 (55,000 fL) from their apertures. Also, the light sources should be configurable into multiple sets (triads) of RGB for the formation of three separate colors within each pixel. The illumination system must be synchronized with the formation of the image on the LCD such that the correct sets of lamps turn on with the appropriate image being displayed on the LCD.

After examining the most promising options available, a configuration of controlled flashing aperture fluorescent lamps was selected for the breadboard because it would also allow insight into future technical and commercial feasibility. Bench modeling was done with shutters and colored filters in order to refine specifications for the fluorescent lamps.

DTI constructed a test bed to qualify fluorescent lamp performance. The test bed consisted of drive circuitry to control up to nine lamps, flexible mounting to evaluate various triad configurations, and apparatus to evaluate chromaticity, luminance, and speed. Cold cathode and hot cathode lamps were identified as two alternatives for lamp sources. Due to the intended breadboard design requirement of thirty-six to seventy-two individual lamps across a 30 cm wide area, DTI investigated the thinnest possible lamp sources. Off-the-shelf hot cathode lamps are available at .7 cm diameter whereas off-the-shelf cold cathode lamps are available at .32 cm diameter. Given lamps of .32 cm diameter, thirty-six individual lamps would easily fit in the 30 cm wide area. The effort to fabricate a hot cathode fluorescent lamp in the .32 cm diameter range was considered beyond the scope of the project if cold cathode lamps could in fact be strobed. DTI obtained several sample cold cathode lamps with various phosphors to evaluate the ability to effectively strobe them at the required rate of 30 flashes per second with a flash duration of 1 - 2 ms. Using the test bed, the cold cathode lamps were configured to be strobed. The lamps were successfully strobed at a rate of approximately 30 flashes per second with a flash duration of 1 - 2 ms. Under the strobing conditions, the decay curve is initially much faster than in the non-strobed case; it dropped at an extremely fast rate (< 1 ms to 1/e) then trailed off in a longer slow decaying tail.

From the experiment it was determined that cold cathode lamps can be strobed and given phosphors with decay times of 2 - 4.0 ms, this approach would work.

Phosphors were specified and fast off-the-shelf RGB phosphors were located. DTI subcontracted the fabrication of prototype red, green, and blue cold cathode fluorescent lamps. When tested, the prototype lamps met and actually exceeded the on/off requirements.

The lamps had the following turn on and off times:

	On Time	Off Time
Red Lamp	< 2.0 ms	< 2.3 ms
Green	< .1 ms	< .1 ms
Blue	< .1 ms	< .1 ms

Neither luminance nor chromaticity requirements were met. Luminance, which was significantly below required levels, was somewhat expected as the prototype lamps were non-aperture. Aperture lamps which are designed to maximize light output, typically provide 1.8 times standard lamp luminance. Chromaticity levels for blue and red appeared less saturated than expected and the green phosphor had a red spike which produced a yellowish tint. Further investigation into obtaining RGB phosphors that more accurately met requirements did not yield any off-the-shelf answer. DTI therefore set out on a dual strategy. The first strategy was to develop an illuminator that could closely emulate the ideal RGB phosphor configuration. This would allow the breadboard to be constructed and evaluated given some tradeoffs due to the emulated illuminator. The second strategy was to quantify the development of an ideal RGB phosphor configuration and assess future implementation.

The RGB illuminator developed for the breadboard included a combination of colored filters and colored phosphors as a means to simulate the most promising RGB technology.

The illumination system consists of thirty-six vertically oriented fluorescent cold cathode aperture lamps spaced across the rear of the LCD. The lamp bank consists of twelve sets (triads) of lamps with each set having a red, green, and blue lamp. The lamps were arranged in an opaque channeled mask to ensure light did not emanate from areas other than the lamp apertures.

The subcomponents for the illumination system had the following key characteristics:

(1) **Lamps** - The lamps are 10 cm long and .32 cm in diameter with .175 cm wide apertures to provide maximum luminance within the aperture. The luminance at the apertures of the individual lamps is:

Red = 18,169 cd/m^2 (5,305 fL)

Blue = 9,278 cd/m^2 (2,709 fL)

Green = 10,730 cd/m^2 (3,133 fL)

In order to closely match the required color coordinates, color filters were needed for the green and blue lamps. Analysis of lamp spectral output and various filters indicated that it was possible to match the required color coordinates. The blue lamps were filtered with GAMACOLOR 106 and 470 which had a transmission of 63.2%. The green lamps were filtered using an OCLI CYAN DICHROIC filter which was 80% transmissive.

The resultant luminance and color coordinates were as follows:

Red =	18,169 cd/m^2 (5,305 fL)	u'=.399, v'=.512
Blue =	5,863 cd/m^2 (1,712 fL)	u'=.120, v'=.332
Green =	7,083 cd/m^2 (2,068 fL)	u'=.136 v'=.572

(2) **Lamp Drivers** - In order for control versatility of the illumination array, each color group is driven individually. A commercially available lamp driver which operates from 28 Vdc and provides a 50 kHz frequency to the lamp was chosen. The lamp driver vendor tested the lamps and modified a standard lamp driver to suit this application. Key specifications for the lamp driver are:

Input voltage 28 ± 10% Vdc
Open Circuit Output voltage 900 Vrms
Output Current limited to 19 ma ± 1 ma
Efficiency 80% at full load
Frequency 50 kHz

(3) **Synchronization Control** - After an image has formed on the LCD, one lamp in each of the twelve sets will flash (each set contains one red, one green, and one blue lamp). The lamps cycle through three different flash patterns (R,G,B; B,G,R; B,R,G). In order to synchronize the lamps with the image formation, controls were built into the framestore. There are two time delays involved in synchronizing the lamps to the image. One is an image forming delay that starts when the last column of the image is written. It is adjustable in 0.5 ms increments from 0 to 3.5 ms. The second time delay controls the length of time the lamps are on. This time starts as the image forming delay ends. This is adjustable in 1 ms increments from 0 to 7 ms. Due to the red lamp having a slower turn off time than the green or blue, control signals were built into the framestore firmware that turned the red lamps on 1 ms prior to the green and blue, and off 1 ms prior to the green and blue. There is also control of the drive current of the lamps in order to change the luminance value of each of the colors to produce white light and this is built directly on the lamp board.

Calculations were performed using the filtered spectral output of the lamps to determine the relative luminance required for each lamp in order to produce white light with coordinates of u'=.209 and v'=.464 to match Air Force specifications. Measurements of light output from groups of red, green, and blue lamps with filters in place were then performed to determine the exact balance required.

The balancing required that the red lamps be set to 84% of the value of green and the blue lamps to 68% of the green. The resultant luminance after balancing was as follows:

Red =	5,949 cd/m^2 (1,737 fL)	u'=.399, v'=.512
Blue =	4,819 cd/m^2 (1,407 fL)	u'=.120, v'=.332
Green =	7,083 cd/m^2 (2,068 fL)	u'=.136 v'=.572

As can be seen by the data, considerable luminance concessions were made using off-the-shelf lamps and phosphors. The resultant RGB illuminator did provide sufficient capability to validate the FSC concept.

In order to increase luminance and obtain a display with 685 cd/m² (200 fL) of luminance, custom phosphor and lamp development would need to be performed. This will eliminate the need for correction filters, increase lamp luminance, and provide fast turn on/off times which will provide a brighter display. Specifications for custom phosphors were developed and a program designed to investigate and identify phosphors that could achieve standard NTSC color coordinates without filters, possess the rapid turn on/off times, and luminance necessary for this application was defined in cooperation with the Phosphor Center of Excellence and the David Sarnoff Research Center.

10.1.2 Optics System

The purpose of DTI's FSC optics system is to focus red, green, and blue light sources into sequentially illuminated spots or lines within the LCD pixel boundaries.

Two alternatives for the breadboard were considered. The first was the use of a fly's eye lens array for the creation of either RGB spots or lines within the pixels of the LCD. The second was the use of a lenticular lens array for the formation of RGB light lines.

The most critical specifications for the optics are the pitch, focal length, size of the spot or line, diffraction and scatter of the lenses.

Optics bench modeling was performed to display both patterns of interleaved spots and lines. Modeling performed to evaluate these approaches consisted of light formation within representative pixel boundaries, flicker visibility, and color balance. Each approach supports both a reduction in frame rate requirements for flickerless viewing and no perceivable image breakup. Both approaches could create spots or lines on the order of 7 μm width.

Given DTI's existing experience with lenticular lenses, the fly's eye approach was selected in order to qualify its optical performance along with its manufacturability and commercial feasibility.

The fly's eye lenses must be positioned very precisely and have closely matching focal lengths in order to form light regions (comprised of one red, one green, and one blue) that are aligned precisely and accurately with the LCD pixels. The light regions must have a pitch that is equal to the LCD pixel pitch.

Precise alignment of the light regions to the LCD pixels had to be accommodated. Alignment requirements are dependent mainly on the size of the LCD and the size of the pixels. For the LCD used under the program, once the light regions were positioned they could not be allowed to shift laterally by more than 1/10th of a pixel width or .0025 cm. In addition the light region as a whole could not rotate by more than the .6 minutes of arc; therefore, a solid mounting with a precise alignment mechanism had to be designed for the lens.

The optics system had to image light from twelve groups of three light sources (one red, one green, and one blue), with a pitch of 2.333 cm located 21.0 cm behind the lens, into 800 groups of three light regions within the pixel

layer. Within each of the twelve groups there were three vertical light sources with a pitch of .640 cm and an aperture width of .32 cm.

The optics system had the following key characteristics:

(1) **Fly's eye lens** - The lens is a 134 x 202 epoxy lenslet array molded onto a quartz glass substrate measuring 19.93 cm x 10.03 cm. The lenslets are convex with a square outline so that lenslets are touching on all four sides. The lenslets are sized to .074205 cm x .074205 cm with a pitch of .074205 cm. The lenslet focal length is .0225 cm.

In addition, in order to maximize luminance and prevent uneven illumination, the lens was specified to transmit 96% of the impinging light with variation in transmittance across the display of less than ± 5%. In order to minimize unwanted reflected and scattered light, the use of anti-reflected coated quartz glass substrates for the lens was implemented.

The lenslets only cover 3/4 of the active area of the LCD. The reason that the lens manufacturer could only make this size array was due to a mechanical fixture size limit. An attempt was made by the manufacturer to develop a full 134 x 265 lenslet array using an overlap technique that they devised. However, this resulted in pitch variations for the remaining 1/4 of the lens that could not be tolerated in this application. The manufacturer stated that this could be solved by developing the mechanical structure needed to hold a larger array.

The fly's eye lens was found to spread more light than a lenticular array due to the light being spread in two dimensions rather than one dimension with the lenticular array. An improvement implemented to compensate for this was the mounting of mirrors inside the area between the lamps and LCD.

(2) **Mounting/Alignment** - A lens mount was designed that attached directly to the LCD assembly and contained manually operated adjustment mechanisms for position and rotational adjustments to the required accuracy. The lens mount proved to perform adequately. The system was aligned easily and remained aligned throughout testing and evaluations. Mechanisms were integrated into the mounting to lock down the optics once they were correctly aligned.

The fly's eye technology is rapidly developing with both smaller lenslet sizes and larger substrate sizes evolving. Development of mechanical fixtures to hold the substrates will allow for commercialization of larger arrays in the future. Given satisfactory results with lenticular lenses and ease of current manufacturing, initial commercial efforts would most likely employ lenticular lenses. If a situation arose where a lenticular lens would not work, a fly's eye lens could be used.

10.2 LCD System

10.2.1 LCD

The purpose of the LCD system is to accept RGB video data, convert it into digital data and display it in the form of three composite fields. The LCD has to provide faster pixel response times (3.5 ms) and faster address times (180 Hz) than those present on any commercially available TFT LCD.

Standard LCDs are updated at a 60 Hz rate (16.7 ms) but their pixels take several frame intervals to fully change to the new state. This is not a problem in normal applications because the image is changing at a much slower rate than 60 Hz.

The challenge for this project was to create an LCD that was addressed and had pixel response times several times faster than common off-the-shelf devices.

The David Sarnoff Research Center (Sarnoff) was selected as subcontractor to develop the custom LCD. After exploring several alternatives, Sarnoff concluded that a version of an existing experimental 400 x 800 resolution Sarnoff LCD with very fast operating speeds could be built using a surface mode configuration proprietary to Optical Shields Inc.

Experimentation with single cells, as well as the LCD itself, prior to integration with the electronics led to the expectation that address rates of close to 180 Hz, pixel response times of .5 ms off and 3.5 ms on, a contrast ratio of up to 25:1, and a maximum transmittance of nearly 25%, could be achieved.

An LCD with the following properties was specified:

Resolution:	400 rows by 800 columns
Active area:	10.16 cm by 20.32 cm
Transmittance:	15% minimum

Since the LCD had to be capable of forming at least 180 completely different images every second, the following properties were also specified:

Element Response Time:	3.5 ms maximum
Address rate:	5.6 ms (1/180th sec)
Contrast Ratio:	25:1 minimum

The LCD subcontractor processed two lots of active matrix substrates. As the substrates were experimental in nature, none of the panels operated 100%. The panel chosen for experimentation provided sufficient operation to both evaluate the DTI FSC technique and fast liquid crystal technique embodied in the LCD.

The panel chosen performed as follows:

Address Speed: 180 Hz

Measured Pixel Response:		
Full CLEAR to 90% DARK	-	.5 ms
Full DARK to 90% CLEAR	-	3.5 ms
Measured Contrast Ratio:	-	46:1
LCD Transmittance:	-	15%

Visual anomalies:

The LCD possesses numerous columns and rows that do not function. Visually, the line outs form an apparent grid pattern that hinder the performance testing of the breadboard. There are approximately 50 columns and 20 rows that are not functioning properly. The primary reason for the high number of line outs is poor interconnects between the electronics and the LCD. This connection process is done through the use of flex leads with a pitch of .0238 cm. Unfortunately the leads obtained by the manufacturer did not precisely match the pitch of the LCD receiving pads. This required a "trial and error" approach to align and bond the electronics to the LCD. The combination of this fine pitch with the delicacy of the AM substrate have made this flexing process highly error prone. Several different techniques and processes were experimented with to minimize the risk of breakage and improve the accuracy of connection. The leads for this LCD have been attached and reattached several times attempting to achieve the exact alignment of the flex leads to the receiving pads. In the process, some of the aluminum contact pads have become smeared in the area between the flex and the edge of the LCD top plate and have caused the line shorts. Some of the columns and rows that are not functioning have no voltage applied to them so they are in an intermediate state which is between clear and opaque and allows the transmittance of some of the light through them. There are also columns that are flashing intermittently.

10.2.2 Framestore

The purpose of the framestore is to act as a buffer and data translator between the image generation system and the LCD display. The framestore captures video data, in the form of three fields (RGB), from the image generation system at a rate of 30 Hz. The framestore takes in standard video input data formatted a row at a time, stores it, formats the data for DTI's FSC pattern, and writes the data out to the LCD. The framestore generates and sends control signals to the LCD to control the operation of the LCD. The framestore also controls the lamp flash sequence with the data placement on the LCD.

The following design goals were established for the framestore.

Dynamic Imagery
The framestore would be capable of accepting and translating dynamic imagery data.

DTI FSC Illumination Technique
The framestore would be designed to control an illumination array comprised of the DTI FSC technique specifically.

LCD Control in the Framestore
Control codes would be sent with each column of data to completely govern the LCD. Operations such as shift registers, flush sequence and column driver functions would reside in the framestore.

Due to the high speed of incoming video data, a scheme was designed in which data was sampled every other bit every other frame. In this manner, data is sampled at a 32 MHz rate and it takes two frames to get a complete set of data from the Image Generation System. This gives a complete frame at a 30 Hz rate. The framestore is responsible for the formatting of row orientated inputs into column oriented outputs of the imagery from the image generation system for DTI's FSC illumination technique along with interleaving the proper columns of color data. Through the use of PROMS, the framestore stores control codes and data translation parameters that are responsible for adding the proper control codes to each column of data and converting linear luminance input data into weighted data to match LCD characteristics.

Synchronization of the high speed, non standard video data from an Indigo workstation required the location of a state-of-the-art video sync IC that could operate at the high speed required. To make the correct lamps come on behind the correct data required coordination of two microprocessors plus a great deal of high speed logic. One microprocessor controlled which color data went to which column; the other controlled flashing of the lamps so that lamp color matched data color. Most of the high speed logic was 74F series logic ICs. The recent availability of high speed programmable logic devices would allow a major reduction in chip count for the framestore. Double buffered RAM was used in order to separate address function of reading and writing data. Swapping of buffered data was controlled at the vertical sync of the incoming data. Once the complete system was up and running, careful shaping of the write clock pulses was required for consistent operation.

The framestore operated correctly and the data was presented in the correct format to the correct columns and flashed the corresponding lamps. The framestore met the performance goals of the system. Data rates that were adjustable from 10 to 180 Hz were provided. The synchronization of the lamps and the LCD to the framestore worked as designed and allowed the needed versatility.

10.3 Image Generation System

The purpose of the image generation system is to provide a variety of graphical images for use in testing and validating individual components, such as the LCD, and for evaluating and demonstrating the performance of the completed system. The image generation component is comprised of the hardware and software necessary to render images for the prototype display.

The most critical requirements are that the image generation system generate RGB signals and have a resolution of 1024 x 768 with a data rate of 64 MHz (15.6 ns).

An SGI Indigo was used as the image generator which had the versatility to generate four different types of images: computer-generated stills, computer-generated animation, raster images (images saved as pixel images), and live video. No special formatting was done to the images except for resizing. Images were resized from 768 x 1024 to 384 x 800 to match the window of the display.

Custom software and images were developed to support component level validation, system testing, and demonstration. These included:

Test images such as full white screen, black screen, gray bars, color bars, alternating white and dark bars for the testing of transmittance, uniformity, gray level performance, and contrast.

Various wire frame images for image quality observations.

All software code is written in Silicon Graphics C.

The image generation system functioned as designed and was able to produce the test and demonstration imagery necessary to validate the prototype display. Through the use of an Indigo Video Adaptor Board (#D5-IVID-2.0), we were able to play VCR tapes through the SGI and display them on the breadboard in order to evaluate live video.

10.4 Integrated Components Test

Assembly of the Lamps, Optics, and LCD was completed and the system was debugged, and tested. After initial adjustments, observations indicated that all elements were operating in synchronization. The system was able to generate, capture and synchronize high speed image data to the LCD and illumination. The complete prototype system operated with the following characteristics:

<u>Display Size</u>

The active area of the display is approximately 9.94 cm x 14.98 cm as dictated by the lens array.

<u>Display Chromaticity</u>

The display is full color as produced by the FSC technique.

<u>Imagery Capability</u>

Images can be displayed in either static or dynamic mode through user controls. Live animation videos can be played through the image generator and displayed on the breadboard. The color bar image consists of a grid pattern of various colors and can be adjusted for different levels of red, green, and blue.

<u>Gray Level</u>

There is fairly good gray level performance with the system. There are approximately eight gray shades per color.

<u>Full Resolution</u>

Using this FSC illumination technique, images are produced at full LCD pixel resolution with each pixel being its own RGB element.

Test Apparatus

A vibration system which roughly simulates the shake and vibration conditions of an air craft and highlights the effects of image break-up was designed. The system is capable of vibrating a mirror in the horizontal or vertical directions at user controllable frequency, displacement and G-force ranges. This allows the viewer to look into the mirror which is vibrating, therefore simulating viewer and or display movements.

In spite of anomalies, the integrated prototype functioned adequately to allow visual evaluation and performance testing of DTI's FSC illumination technique.

11. TESTS AND EVALUATIONS

Tests and evaluations were broken up into two separate events. The first served to define illumination system requirements for the breadboard and was performed using a simple bench model. The bench model was comprised of steady white lamps, color filters and shutters. The second round of testing was done with the breadboard. This testing was subdivided into tests with the illumination system exclusively and tests with a fully integrated system. A discussion of all testing follows.

11.1 <u>BENCH MODEL TESTS</u>

11.1.1 Color Breakup from Illumination Unevenness

Tests were performed using the bench model to analyze the effect on color breakup when variations in luminance were found between flashes. The following is a summary of those tests.

The DTI FSC filter pattern was set up in front of the lamp bank and diffuser, without any effort to reduce "hot spots" or otherwise optimize the system. Shutter speed was adjusted so that no flicker was visible.

The luminance provided at the center of the screen, by each color filtered section on each shutter, was measured. The variation between illumination provided by different filters of the **same** color in front of different shutters was found to be ± 24% for the red shutters, ± 32.5% for the green, and ± 13% for the blue. The overall screen luminance was measured to be 11 cd/m^2 (3.2 fL).

Using the vibration system, color breakup was visible and pronounced at high amplitude vibration settings. Various vibration settings were tested and the setting range where breakup was very obvious was noted. As suspected, red was the most obvious color, with some green visible and blue hardly visible.

Luminance measurements were used to mask off each filter in order to make the illumination provided through all of them equal. After some experimentation with masking, then measurement and observations, it was found that color breakup became completely invisible within the full vibration range tested. Individual colors were measured to vary by ± 4% in the red, ± 7% for green, and ± 6% for blue.

Since red is the most visible, it was decided to unmask one of the shutters in increments until color breakup became visible. It was predicted that the luminance variation tolerance for the green and blue should be above this value, therefore keeping all colors within the allowable luminance tolerance for red should ensure that no color breakup is seen.

The brightest red filter was unmasked and the luminance values remeasured. A luminance variation of ± 11.2% was the measured variation for which red color breakup was slightly visible and was eliminated at a 4% variation. Center screen luminance after masking was found to be 7.7 cd/m^2 (2.25 fL). The overall chromaticity value was calculated to be roughly u'=.206, v'=.476, which is close to pure white. A variation of ± 8%, which was in between these two limits, was specified for the allowable luminance variation for individual colors during individual flashes to ensure no color breakup would be present. This value must be compared to the constraints on variation imposed by Air

Force chromatic and overall illumination evenness requirements to determine which one imposes the most stringent constraint.

11.1.2 Color Randomization

Initial theory suggested that complex, randomized patterns of colored spots would be necessary to eliminate visible color breakup. Tests with the simplest pattern were sufficient to eliminate color breakup and greatly lower critical flicker frequency to the predicted values, as long as illumination and color coordinates in successive flashes were nearly equal. It was experimentally validated that even simple line patterns work as well as patterns of colored spots. Such lines are much easier to form than spot patterns and allow for simplified illumination and optics. It was determined that more complex, randomized color patterns would be harder to generate and would complicate the illumination system without any significant benefits. Therefore, no further work was done to investigate more complex patterns of spots.

PROTOTYPE BREADBOARD TESTS

Two sets of breadboard experiments were done, one with and one without the LCD. During these experiments, five test subjects were used to evaluate the visibility of flicker, beta movement, and color breakup effects.

11.2 Tests of the Illumination System Alone

11.2.1 Flicker Visibility

Five test subjects viewed the 10.0 cm x 15.0 cm area of the fly's eye lens and diffuser from a distance of 76 cm, illuminated at a luminance of 44.5 cd/m^2 (13 fL) average, with DTI's FSC patterns being displayed. The subjects reported that flicker became visible at 87 Hz maximum, with an average of 83 Hz and a minimum of 80 Hz. The following data was recorded:

Table 4
Illumination System Critical Flicker Frequency Measurements

Subject #	Luminance	Flash rate	Flash frequency
1	39.4 cd/m^2	12.0ms	83Hz
2	41.1 cd/m^2	12.5ms	80Hz
3	48.0 cd/m^2	12.0ms	83Hz
4	48.0 cd/m^2	11.5ms	87Hz
5	41.1 cd/m^2	12.0ms	80Hz

Rates and frequencies refer to individual flashes, equal to one third of a three flash cycle.

11.2.2 Beta Movement

Beta movement refers to the illusion that causes sequentially flashing light sources to appear as steadily moving light sources, as do the light bulbs on an old fashioned theater marquee or the LEDs in a modern moving message sign.

No subjects reported beta movement visibility at the critical flicker frequencies.

11.2.3 Color Breakup

All five test subjects reported that color breakup was not noticeable at the edges of a movable aperture placed in front of the system when DTI's technique was used, but was visible when conventional FSC illumination was used.

11.3 Tests with the LCD in Place.

11.3.1 Flicker

Due to the multiple flashing line outs present on the LCD, it was necessary to use one of several small areas that were defect-free in order to test for flicker visibility. Ten observers seated at a distance of 76 cm were shown white, red, green, and blue fields in a 10 cm x 1.5 cm area of the LCD, with a white luminance in the 6.8 - 13.6 cd/m^2 (2 - 4 fL) range. In order to determine when flicker might become visible on a larger screen, observers were asked to gaze at points 10 cm to either side of the field so that the image field would appear in the same area of their retina as would the edge of a larger screen 20 cm across. Flicker generally becomes more easily visible away from the gaze point.

The critical flicker frequency for a white field was measured to be a maximum of 88 Hz, with an average of 77 Hz and a minimum of 65 Hz.

The following data was recorded:

Table 5
Breadboard System Critical Flicker Frequency Measurements

Subject	Flicker Detected at	
	Flash Rate	Frequency
1	15.4 ms	65 Hz
2	14.4 ms	69 Hz
3	11.4 ms	88 Hz
4	12.4 ms	81 Hz
5	13.4 ms	75 Hz
6	12.4 ms	81 Hz
7	13.4 ms	75 Hz
8	14.4 ms	69 Hz
9	11.4 ms	88 Hz
10	13.4 ms	75 Hz

Primary color fields seemed more flicker sensitive. The worst case was the green field, for which flicker was detected at a maximum of 96 Hz, an average of 84 Hz, and a minimum of 69 Hz. Increased sensitivity for the primary colors is believed to be due to small variations in the intensity of different lamps. When a primary color was being displayed, the light from a fewer number of lamps was being seen, thus the variations in the luminance of

individual lamps caused a greater percentage of overall luminance variation from the average. The green lamps were found to possess the greatest variation.

The following data was recorded for the primary color fields.

Red Illumination

Table 6
Red Illumination Critical Flicker Frequency Measurements

Subject	Flicker Detected at	
	Flash Rate	Frequency
1	15.4 ms	65 Hz
2	13.4 ms	75 Hz
3	11.4 ms	88 Hz
4	11.4 ms	88 Hz
5	10.4 ms	96 Hz
6	10.4 ms	96 Hz
7	10.4 ms	96 Hz
8	14.4 ms	69 Hz
9	12.4 ms	81 Hz
10	12.4 ms	81 Hz

Green Illumination

Table 7
Green Illumination Critical Flicker Frequency Measurements

Subject	Flicker Detected at	
	Flash Rate	Frequency
1	14.4 ms	69 Hz
2	13.4 ms	75 Hz
3	11.4 ms	88 Hz
4	10.4 ms	96 Hz
5	10.4 ms	96 Hz
6	12.4 ms	81 Hz
7	10.4 ms	96 Hz
8	11.4 ms	88 Hz
9	14.4 ms	69 Hz
10	11.4 ms	88 Hz

Blue Illumination

Table 8
Blue Illumination Critical Flicker Frequency Measurements

Subject	**Flicker Detected at**	
	Flash Rate	**Frequency**
1	15.4 ms	65 Hz
2	14.4 ms	69 Hz
3	11.4 ms	88 Hz
4	11.4 ms	88 Hz
5	12.4 ms	81 Hz
6	12.4 ms	81 Hz
7	10.4 ms	96 Hz
8	12.4 ms	81 Hz
9	12.4 ms	81 Hz
10	13.4 ms	75 Hz

11.3.2 Beta Movement and Jitter

Beta movement was reported by one of the ten subjects during saccades when the display was running just under the subject's critical flicker frequency. One other subject reported a phenomena described as lines becoming "temporarily visible" during saccades even at the fastest speeds. No jitter was reported by any of the ten subjects.

11.3.3 Color Breakup

No one reported color breakup during saccades, during image movement in video images, or when viewing still images through a vibrating mirror that made the screen images appear to move back and forth across .8 cm at a rate of 30 Hz. No breakup was seen in areas of the LCD that were operating properly, but it was present in columns and groups of columns that were not operating properly.

11.3.4 Frame-Sequential Image Breakup

Another type of visual artifact evaluated was image breakup in moving objects. This visual artifact can be caused whenever a frame is made up of two or more sequential subfields (as is the case with theater movies and interlaced CRTs). This artifact was not observed by any of the ten subjects, but results of the test are preliminary due to poor LCD performance across much of the LCD. Theory predicts that it should be present to a degree similar to that seen on interlaced CRTs or theater movies. Further research with an improved display would allow for the collection of conclusive data on whether or not this artifact is present using this technique.

11.3.5 Screen Luminance Variations

Luminance on the left side of the breadboard was measured to be generally 70% brighter than the right side with the illumination at the preferred 88 Hz speed. One cause of this effect was the variations in LCD transmittance

across the display. Another cause was the display being addressed from left to right which creates a variation in the amount of time pixels were both in the on state and illuminated. The amount of variation is dependent on the frame rate and the lamp turn on timing. This effect could be significantly reduced by illuminating the display in sections following the scan of those sections. This technique has been experimentally demonstrated on other DTI displays.

11.3.6 Illumination Evenness

A visible periodic unevenness in color coordinates that matched the pitch of the various colored lamps was seen when displaying a white screen when the illumination system and LCD were first mated. Experimentation along with observations under a microscope proved that a very weak diffuser (< 5 degrees half angle) placed directly on front of the LCD glass would eliminate this effect without degrading the image resolution (i.e., the light lines, being close to the diffuser, are not diffused into one another).

11.3.7 Color Quality

All primary and secondary colors were successfully displayed separately and together in a checkerboard pattern on the display. The ability of the system to create any color in the color gamut was successfully demonstrated. This color generation was performed through the use of software that allowed the user to vary the amount of red, green, and blue in a field. Overall, the visual impact seemed to be quite good to most observers. Measurements by the lamp supplier had indicated that the color coordinates of the lamp and filter combinations used were close to those specified by the Air Force.

One artifact of color quality that was observed was the presence of color shifts of the green to more of a blue color when the display was viewed from angles beyond approximately ± 20 degrees in the vertical and horizontal directions. A dichroic filter was used over the green lamps to achieve the desired color coordinates. The behavior of this type of filter in terms of the percentage of light reflected or transmitted at various wavelengths changes according to the angle of incidence of the light onto the filter. If one views the green lamps through the filters from more than about 20 degrees off axis, they appear noticeably bluer than when viewed from on axis. The further off axis one moves, the bluer they appear. The use of custom phosphors which would eliminate the color filters would in turn eliminate this artifact.

12. EFFICIENCY MODELING

Paramount to the technical feasibility of this FSC technique is the overall efficiency in which RGB light lines or spots are delivered to subregions of pixels in a frame-sequential manner. The benefits of improved resolution and luminance through the removal of color filters can only be realized if luminance to power ratios can be maintained and required display luminance levels can be met. Being a unique concept, data on system efficiency needed to first be established and then analyzed to assess overall efficiency.

Several parameters must be considered when evaluating the efficiency of this approach. To that end, a series of models were produced and an equation was developed to evaluate variations in key parameters and their effect on system efficiency.

The behavior of the LCD and light sources was modeled mathematically using the following assumptions:

(1) The LCD turn on was an exponential function.

(2) The lamp turn on and off was instantaneous - essentially a square wave.

(3) The lamps were always turned off at the same time the LCD was blanked.

All three assumptions were close to reality. The turn on and turn off curves of the LCD, as measured with an oscilloscope, are of the general shape of an exponential curve. The curves actually reach full on and full off after some time period, instead of approaching them exponentially forever. It was found that the resulting differences between calculated values and reality due to this factor were small.

The lamp turn on and turn off times, though not truly instantaneous, were short compared to the total on time of the lamps over much of the range tested. Lamp turn on and off times were below .1 ms for the green and blue phosphors, and slightly over 2 ms for the red. The lamps were, in fact, turned off when the LCD was blanked.

Figure 14 illustrates the operation of the LCD and light sources. At the end of each frame, the LCD is blanked so that all of its pixels are driven to full off. Next, the LCD is addressed column by column starting with the leftmost column. As each column is addressed, its pixels start changing to form that column's part of the next image. At some time after the scan is complete, but not necessarily before all the pixels on the right side of the display complete their change, the lamps are turned on. The lamps are then turned off at the same time the LCD is blanked again. The turn on curve of a representative pixel at the right side of the display is shown as a solid line. The dotted line represents the turn on curve of a pixel at the left side of the display.

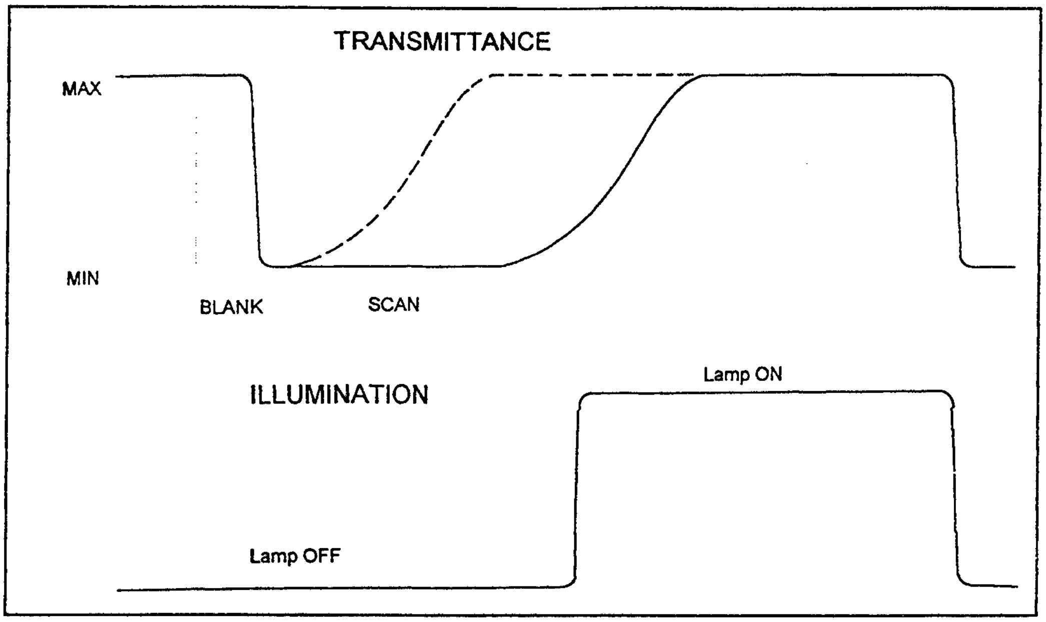

Figure 14
LCD and Light Source Operation

12.1 Display Luminance

Overall luminance under these conditions was calculated by starting with the exitance of the lamps, in candelas per meter squared (cd/m²), and figuring out losses in exitance due to the spread of the light caused by the fly's eye lens, and the measured losses at the fly's eye lens and diffuser. Next, the integral of this quantity times the transmittance of the LCD as the pixels turned on during the lamp on period was calculated, and finally this was divided by the total period for one field to yield the average luminance as perceived by an observer, expressed as an average exitance in cd/m².

The resulting equation for the luminance is:

$$\text{Display Luminance} = 3 \times LBR \times \frac{LW}{LP} \times DIFT \times LENT \times LCDT \times \left[\frac{(SP + PP - LON) + \dfrac{e^{(-CONST \times (SP + PP - SP/NSEC))} - e^{(-CONST \times (LON - SP/NSEC))}}{CONST}}{(SP+PP)} \right]$$

where:

- SP = the time when the address of a pixel begins, the "begin address" axis on the graphs.
- PP = the pause period, or time period between the pixel address and the next blank.
- LW = lamp width that is exposed allowing light to exit the lamp.
- LBR = average exitance for the red, green, and blue lamps.
- LP = lamp pitch distance between adjacent lamps of the same color.
- DIFT = diffuser transmittance.
- LENT = lens transmittance.
- LCDT = LCD transmittance when full on.
- LON = time when lamp turns on.
- CONST = a constant of .658 which causes the curve to reach 90% of LCD transmittance (LCDT) in 3.5 ms.

In addition, the time from one blank to the next or in other words the frame period (SP + PP) is held constant at 11.4 ms.

In the equation, the factor (3 X LBR) represents the fact that three sets of lamps are on at any given time. The factor (LW/LP) indicates the fact that light from a given lamp is spread out, as seen by an observer's eye, across a width approximately equal to the pitch between two lamps of the same color. Thus luminance per unit area decreases according to the ratio of the lamp width to the area over which the light seems to be spread. The quantities LENT and DIFT simply represent the percentage of incident light that is transmitted through the lens and the diffuser. The quantity LCDT and the section of the equation in parenthesis represents the integral of the transmittance curve of the LCD during the time that the lamp is on (SP+PP-LON), which varies by exponentially approaching LCDT after the address. The equation is divided by the frame period (SP + PP) to yield the average amount of light exiting the display over the entire frame period. This represents the luminance that the observer will perceive. Three system models were derived and calculations of luminance were made. The first model involves the actual values from the optimized breadboard. The second model is for a "best case" system using ideal parameters. The third model involves "most likely" parameters.

Model 1 - Luminance Calculation for the Optimized Breadboard

The following values equal the best measurements taken on the display. The values obtained from operator settings are explained below.

SP	=	0 ms
PP	=	11.4 ms
POFF	=	.5 ms
PON	=	3.5 ms
LW	=	.32 cm
LBR	=	5,952 cd/m^2 (1,738 fL)
LP	=	7.0 cm
DIFT	=	.87
LENT	=	.91
LCDT	=	.15
LON	=	7.4 ms

The value of the begin address (SP) chosen simulates conditions on the left side of the display, where the display is as bright as possible due to complete pixel change occurring before the lamps turn on. The value of 11.4 ms for the time between subsequent addresses of each pixel (PP) was used because it is the maximum time period that was experimentally determined which produced flicker-free images for most test subjects. The lamp turn on time (LON) of 7.4 ms is the earliest possible turn on time allowed by the lamp electronics.

Inputting these values into the equation yields:

Model 1

$$\text{Display Luminance} = 3 \times 5952 \times \frac{.32}{7.0} \times .91 \times .87 \times .15 \times \left[\frac{(0 + 11.4 - 7.4) + \dfrac{e^{(-.658 \times (0 + 11.4 - 0/1))} - e^{(-.658 \times (7.4 - 0/1))}}{.658}}{(0 + 11.4)}\right]$$

$$\text{Display Luminance} = 96.96 \times \left[\frac{(4.0) + \dfrac{.00056 - .007}{.658}}{11.4}\right]$$

Display Luminance = 33.93 cd/m² (9.906 fL)

Using the equation, the luminance was calculated to be 33.93 cd/m² (9.906 fL). The display luminance was actually measured to be 38.0 cd/m² (11.1 fL). A 5.84% deviation between the measured value and the model prediction was found and considered acceptable given potential variations in lamp luminance (LBR) as display temperature fluctuated, LCD nonuniformity, and experimental error.

Model 2 - Luminance Calculation for a "Best Case"

The following values are optimized system parameters given improved lamps, improved LCD transmittance, and an increase in the lamp on time.

SP	=	0 ms
PP	=	11.4 ms
POFF	=	.5 ms
PON	=	3.5 ms
LW	=	.5 cm
LBR	=	41,099 cd/m² (12,000 fL)
LP	=	7.6 cm
DIFT	=	.87
LENT	=	.91
LCDT	=	.25
LON	=	1.2 ms

The lamp width (LW) of .5 cm represents the width of an aperture lamp with a known lamp luminance (LBR) of 41,099 cd/m² (12,000 fL) using a commercial phosphor mixture. Assuming custom RGB phosphors could achieve this value, average lamp luminance (LBR) was set to 41,099 cd/m². The lamp pitch (LP) of 7.6 cm is what the pitch would have to be if these lamps were used and mounted as close together as possible. The lamp turn on time (LON) of 1.2 ms represents the amount of time that a lamp could remain on if lamps were turned on sequentially starting at the left and moving to the right. This would allow .25 cm wide sections of the LCD to be illuminated in succession as soon as all the columns in each section were addressed, instead of waiting for all the columns to be addressed and turning on all the lamps. The LCD transmittance (LCDT) was set to 25% due to experimental LCD samples that reached 25%.

Inputting these values into the equation yields:

Model 2

$$\text{Display Luminance} = 3 \times 41{,}099 \times \frac{.50}{7.6} \times .91 \times .87 \times .25 \times \left[\frac{(0 + 11.4 - 1.2) + \dfrac{e^{(-.658 \times (0 + 11.4 - 0/1))} - e^{(-.658 \times (1.2 - 0/1))}}{.658}}{(0 + 11.4)} \right]$$

$$\text{Display Luminance} = 1606.3 \times \left[\frac{(10.2) + \dfrac{.00056 - .454}{.658}}{11.4} \right]$$

Display Luminance = 1340 cd/m² (391.3 fL)

Using the equation, the luminance was calculated to be 1340 cd/m² (391.3 fL). This is a significant increase and is almost twice the 685 cd/m² (200 fL) requirement.

Model 3 - Luminance Calculation for "Most Likely" System

The following values represent parameters required to achieve 685 cd/m² (200 fL) luminance. These parameters are all considered technically feasible and are less stringent with regard to lamp luminance, LCD transmittance, and lamp on time than those in Model 2.

SP	=	0 ms
PP	=	10.0 ms
POFF	=	.5 ms
PON	=	3.5 ms
LW	=	.5 cm
LBR	=	28,769 cd/m² (8,400 fL)
LP	=	7.6 cm
DIFT	=	.87
LENT	=	.91
LCDT	=	.20
LON	=	1.2 ms

In this model, the time between addresses of the same column (PP) was dropped back to 10 ms to allow the display to remain flicker-free even in the presence of significant variations in luminance between lamps.

Lamp luminance was dropped back to reflect the Air Force's preference for power savings rather than luminance significantly in excess of 685 cd/m² (200 fL), given a choice between the two. The LCD transmittance (LCDT) was set to 20% which was between the 15% for the experimental panel for this prototype breadboard and 25% for the experimental LCD samples.

Inputting these values into the equation yields:

Model 3

$$\text{Display Luminance} = 3 \times 28{,}769 \times \frac{.50}{7.6} \times .91 \times .87 \times .20 \times \left[\frac{(0 + 10.0 - 1.2) + \dfrac{e^{(-.658 \times (0 + 10.0 - 0/1))} - e^{(-.658 \times (1.2 - 0/1))}}{.658}}{(0 + 10.0)} \right]$$

$$\text{Display Luminance} = 899.0 \times \left[\frac{(8.8) + \dfrac{.0014 - .454}{.658}}{10.0} \right]$$

Display Luminance = 730 cd/m² (213.0 fL)

Using the equation, the luminance was calculated to be 730 cd/m² (213.0 fL) which supports the feasibility of developing displays meeting desired luminance requirements.

12.2 Illumination Evenness

A second key display characteristic modeled was the illumination evenness across the display.

Illumination evenness could be affected by incomplete pixel turn on in the last parts of the screen addressed prior to the lamps turn on. The result of this would be that one side of the screen would tend to appear brighter than the other.

By using the equation and varying the address time between 0 ms and 5.6 ms for a given lamp turn on time (LON) and a given turn off time (obtained by keeping the frame period, SP+PP constant), apparent display luminance can be calculated for location points from left to right where the LCD is turned on later and later. These luminance points result in a curve of luminance versus the begin address (SP) and provide an estimate of how luminance varies from the left side (0 cm) to the right side (20.0 cm) of the screen. By setting the time when the lamp turns on (LON) at different values, one can obtain a set of curves representing how luminance varies from one side of the display to the other as the lamp is turned on later and later, and thus remains on for shorter and shorter periods of time. The result is the set of curves shown in Figure 15. Each of the curves represent how luminance varies from the left to the right side of the screen given a certain lamp on period (LON).

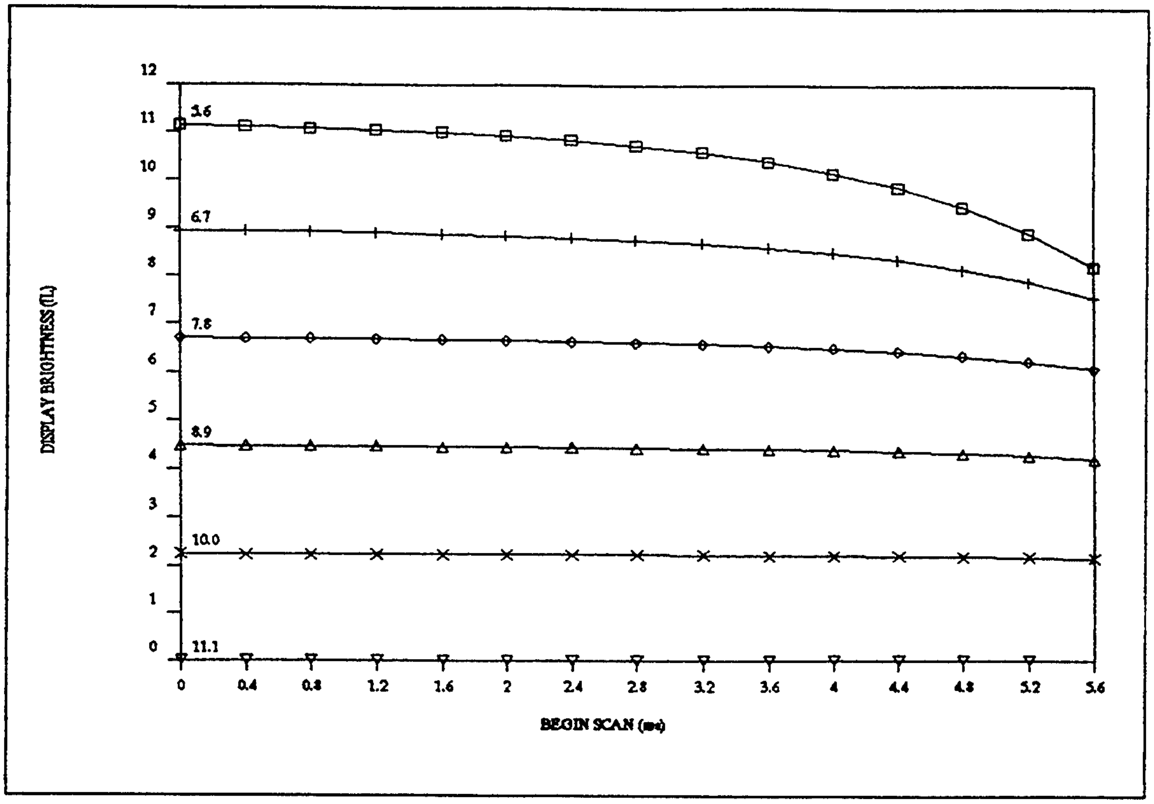

Figure 15
Screen Luminance Calculations versus Lamp On Time

A second set of graphs was generated to model the system luminance using the breadboard prototype lamp turn on and turn off times. The controls on the system allowed the period of time that the lamp was on, represented in the equation by the quantity (SP+PP-LON), to be varied from 1 ms to 8 ms. The point in time when the lamp turns on (LON) could also be varied from 7.4 ms to 14.4 ms after the start of the LCD scan. For the breadboard prototype the turn on time was kept at 7.4 ms after the start of the LCD scan. This was simply the earliest possible turn on time that provided the highest possible luminance. Thus (LON) was set at 7.4 ms in the equation and the amount of time the lamps were on was varied by increasing or decreasing the frame period (SP + PP), as was done on the actual display.

By changing the frame period values between 1 ms and 8 ms in 1 ms intervals, the set of curves shown in Figure 16 was obtained. These curves predicted luminance differences from one side of the display to the other as the frame period was changed.

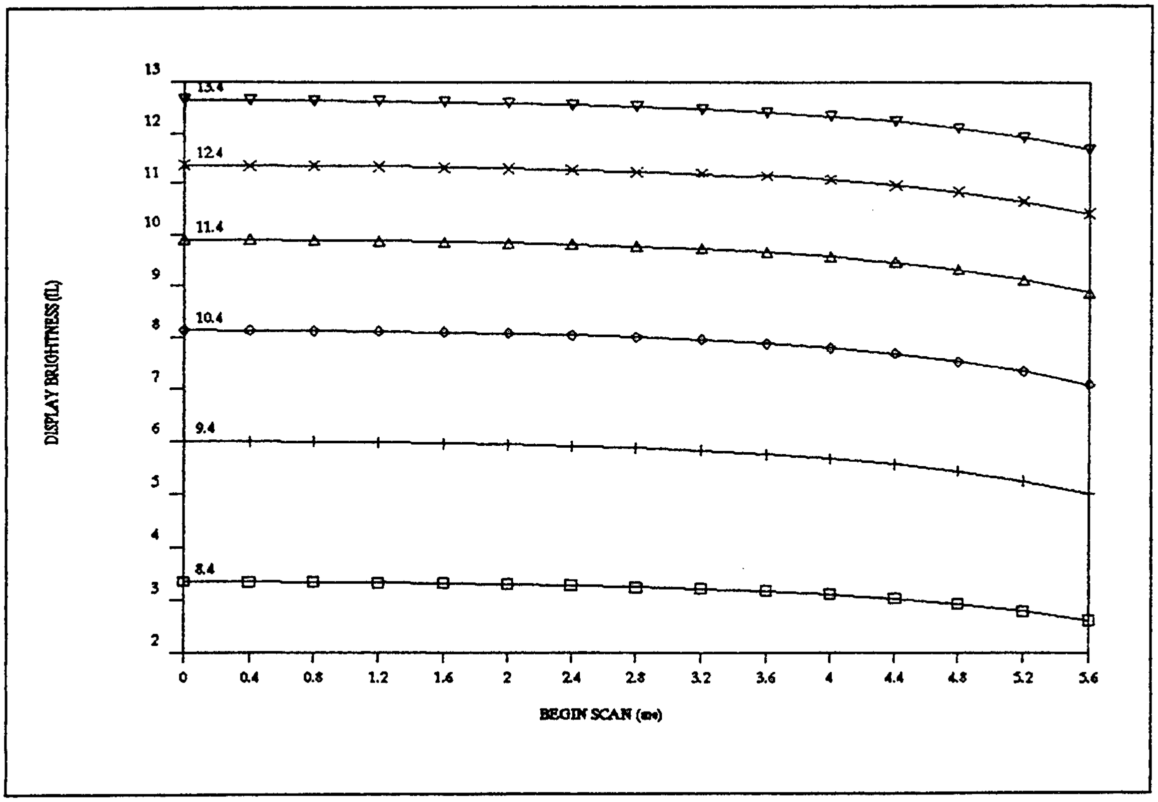

Figure 16
Screen Luminance Calculations versus the Frame Period

The actual luminance values measured are shown in Table 9. Results were close in overall luminance at the maximum values (91% of the measured values) on average but predicted less of a drop off in luminance than was actually observed.

The difference in drop off between predicted and measured values is believed to be due to variation in LCD transmittance. Contrast and transmittance varied across the display, and measurements showed that the luminance was higher on the left side versus the right even when steady light sources were used. The slight drop in luminance on the left edge was due to a dim lamp in the leftmost RGB group.

The predicted low differences in luminance due to incomplete pixel decay at the duty cycles associated with 90 Hz operation suggest that given a sufficiently bright strobed light source (or low luminance requirements) and an LCD with pixel response properties similar to those used here, it may not be necessary to blank separate sections of the LCD or turn on lamps sequentially behind each section. This has the potential to simplify the design of both the LCD and illumination in certain cases. More measurements are needed with a better functioning LCD to verify that this is true in a given case. Multiple blanked sections in combination with illumination that turns on behind each section in succession still has an advantage in terms of achievable luminance, since each lamp can stay on longer.

Readings were taken at a constant lamp surface temperature of 49 degrees C.

Table 9
Breadboard System Luminance Measurements Across the Display

			Distance From Left Edge L	Middle	R
Lamp On	**Lamp Off**	**Duration On**	**30 mm**	**57 mm**	**125 mm**
7.4 ms	8.4 ms	1 ms	12.7 cd/m^2	12.7 cd/m^2	9.9 cd/m^2
7.4 ms	9.4 ms	2 ms	21.9 cd/m^2	22.3 cd/m^2	17.8 cd/m^2
7.4 ms	10.4 ms	3 ms	30.1 cd/m^2	30.5 cd/m^2	25.0 cd/m^2
7.4 ms	**11.4 ms**	**4 ms**	**37.7 cd/m^2**	**38.0 cd/m^2**	**31.2 cd/m^2**
7.4 ms	12.4 ms	5 ms	41.1 cd/m^2	42.5 cd/m^2	34.9 cd/m^2
7.4 ms	13.4 ms	6 ms	47.6 cd/m^2	48.3 cd/m^2	40.1 cd/m^2
7.4 ms	14.4 ms	7 ms	50.3 cd/m^2	52.0 cd/m^2	44.2 cd/m^2
7.4 ms	15.4 ms	8 ms	55.1 cd/m^2	56.2 cd/m^2	46.2 cd/m^2

12.3 Power Efficiency

The ideal Air Force cockpit display would have a luminance of 685 cd/m^2 (200 fL) and a power input of no more than .16 watt per square centimeter. This is contrasted to today's typical levels of 548 cd/m^2 (160 fL) and power input of .47-.62 watts per square centimeter. One can roughly estimate the power required to drive each of the optimized models discussed above and derive the overall efficiency that can be expected with each of them.

The power required to drive an LCD based display can be expressed as the sum of three components:

$$\text{Power} = \text{PLCD} + \text{PFS} + \text{PL}$$

where:

PLCD = power required to run the LCD
PFS = power required to run the framestore
PL = power required to run the lamps

The breadboard model had the following values:

PLCD = 138.0 W
PFS = 10.5 W
PL = 18.2 W

Thus the total power required is 167 W, or .81 W per square cm of display surface .

Eighty-nine percent of this power requirement (149 W) is consumed by the LCD and framestore. Power requirements for the LCD in particular were excessively high because no commercially available LCD driver chips existed to run surface mode LCDs at the required voltages. This necessitated that the system be built using off-the-shelf operational amplifiers that were not specifically designed for this application.

A prototype system optimized for efficiency would still consume more power than a typical commercial LCD due to the larger voltages required for the configuration. At this time only a best guess estimate can be made. A considerable amount of design and development work must be done before a reliable answer can be obtained. A best guess estimate of 20 W for the LCD and framestore is made. This is about twice what would be expected for a conventional TFT LCD and controller running at 11.4 ms per field. Given this power requirement, the breadboard would consume 28.2 watts, or .19 W per square cm at a luminance of 38 cd/m² (11.1 fL).

Estimates of the efficiency achievable with Model 2 and 3 can be made using the breadboard estimate as a starting point. The models differ from the breadboard mainly in lamp luminance (LBR) and lamp duty cycle (SP + PP - LON). In addition the LCD transmittance (LCDT) is 25% in Model 2 and 20% in Model 3. Also, a slightly shorter field (SP + PP) of 10 ms is used in Model 3.

Power to the lamps themselves, which is currently about 18.2 watts, would increase approximately in proportion to the lamp duty cycle and lamp luminance at a given flash frequency. The increase in LCD transparency will result in a proportional drop in power requirements. Power to the LCD and framestore would increase at a rate approximately proportional to the number of fields displayed per second.

Thus in Model 2, the power required to run the lamps (PL) will increase by a factor proportional to:

$$\frac{LBR'}{LBR} \times \frac{LCDT}{LCDT'}$$

LBR = breadboard lamp luminance = 5,952 cd/m² (1,738 fL)
LBR′ = Model 2 lamp luminance = 41,099 cd/m² (12,000 fL)
LCDT = breadboard LCD transparency = .15
LCDT′ = Model 2 LCD transparency = .25

The power required to run the lamps (PL) would increase by a factor of 4.14.

Since the other terms remain the same, the overall power requirements would become Power = (18.2 X 4.14) + 20 = 95 W in Model 2, yielding a power efficiency of .4 W/sq cm at 1,339 cd/m² (391 fL).

In Model 3, LBR′ = 28,769 cd/m² (8,400 fL), and LCDT′ = .20. In addition, a slight increase in LCD and framestore power proportional to 100 Hz (model field rate)/87.7 Hz (breadboard field rate) would be required due to the increased speed at which images are being displayed.

The overall power requirement would therefore be Power = (18.2 X 3.6) + (20 X 100/87.7) = 88 W, or .37 W/sq cm at 730 cd/m² (213 fL).

Thus at 730 cd/m² (213 fL), the estimated achievable efficiency is only slightly better than the .47-.62 W per square cm at 548 cd/m² (160 fL) that is typical of military displays being produced today. It is still far higher than the .16 W per square cm that is desired by the Air Force. Using the model, a display luminance of 548 cd/m² (160 fL) results in an efficiency of .36 W per square cm. This is clearly an improvement to the .47-.62 W per square cm, but still needs some optimization to reach the desired .16 W per square cm. However, the present day military TFT LCD power requirements are

the result of years of development and optimization effort directed at both the LCDs and their illumination systems. Given a sufficient development effort directed toward surface mode LCD technology and the field-sequential color lamp system, power requirements much lower than the estimates made above may be achievable.

13. CONCLUSIONS

Based on experimentation with and observations of the DTI breadboard FSC display, as well as mathematical modeling using the breadboard properties as a baseline, the following major conclusions can be drawn.

The DTI FSC technique produces full resolution color images on a monochrome LCD.

The DTI FSC technique does not create color breakup during saccades or when the display and image vibrate.

The critical flicker frequency for a typical display using DTI's technique will be close to 90 Hz versus 180 Hz for conventional FSC. This translates into a lower operating speed requirement for the LCD potentially simplifying its development.

DTI's technique does not introduce any visual artifacts such as beta movement, and jitter that degrade the image quality.

Baseline data has been gathered and modeled for illumination luminance, evenness, and power efficiency in order to identify parameters that need to be optimized to produce an efficient 685 cd/m^2 (200 fL) display.

Surface mode liquid crystal technology can be used to create LCDs with sufficient operating speeds for the implementation of DTI's FSC technique; address rates of almost 180 fields per second and pixel response times of 3.5 ms can be achieved.

Complex patterns are not needed in order to eliminate color breakup and the simple random pattern works equally well in colored line or spot formations.

REFERENCES

RELATED DOCUMENTATION

[1] 3D Flat Panel Color Display: Requirements Validation Report, Doc. #10105, Rev. 1, July 29, 1993.

[2] 3D Flat Panel Color Display: Acceptance Test Plan, Doc. #10095, Rev. 2, July 1, 1993.

APPENDIX A

ADAPTION OF DTI'S FIELD SEQUENTIAL COLOR TECHNIQUE TO PROJECTION DISPLAY DEVICES

Currently, there are no off-the-shelf LCDs of suitable size and performance to support this FSC technique for direct view applications. Under this program significant advances were made with regard to liquid crystal technology that could make an off-the-shelf solution a future reality.

The David Sarnoff Research Center achieved very fast address rates and pixel turn on and turn off times through use of a surface mode LCD using polycrystalline silicon driver electronics. Polysilicon driver electronics allow very fast address rates commensurate with the pixel response times, combined with fewer interconnections than other TFT technologies and more reliable operation. Address speeds of just under 180 fps were achieved. The response times possible with liquid crystal materials are typically dependent on the thickness of the LC layer, which is determined by the spacing between the glass plates of the LCD.

To achieve the speeds required for FSC, one would normally have to use a very thin spacing, on the order of a few microns. However, maintaining this spacing over the surface area of a typical display would be difficult if not impossible. One alternative is to use a surface mode LC material in which only a thin layer near one of the liquid surfaces is active. Thus, the high speeds associated with a thin LC layer are achieved without having to make the overall LC layer thickness thinner than usual. Easy to maintain glass spacings can be used. Pixels response times of 3.5 ms to full on and .5 ms to full off were achieved using this type of material.

The next logical step is to embody the fast LC technology in a "production quality manufactured" AM TFT panel. This would isolate the fast LC recipe from TFT manufacturing anomalies and allow a true preproduction prototype display to be developed and evaluated for commercial feasibility. This future development effort will require collaboration between DTI, Sarnoff and a to be determined LCD manufacturer.

More immediately, projection grade LCDs and other types of light valves are emerging with suitable performance characteristics to support this FSC technique in a projection implementation. One VGA resolution device is now available off the shelf. These light valves are all small devices being developed for field sequential color projection display systems, such as projection televisions. As such, they are inherently capable of operation at 180 fps, to avoid flicker. One California company now markets such an LCD, a 1.72 cm diagonal reflective VGA resolution device. It uses standard TFT LCD technology and achieves its fast speed through fast LC material in combination with a very thin cell gap, which is easy to maintain over such a small area. A partner in the European Flat Panel Display joint venture has produced and demonstrated a similar 5.0 cm diagonal 180 fps transmissive LCD in the laboratory.

Two other companies, in the U.S. and the U.K., are developing and marketing low resolution (256 x 256) samples of ultra fast reflective ferroelectric LCDs and actively developing higher resolution versions. These LCDs have pixel response times on the order of .1 ms, and can be addressed at rates of several thousand frames per second. The very high speed is used to achieve an adequate gray scale; since ferroelectric LC material is bi-stable, the pixels can be turned to the full on or full off states, but not in between as is required for gray scale. Gray scale is achieved by turning individual pixels off partway through a standard 1/60th second frame. The very fast address rates used allow any of the pixels to be turned off during any one of several dozen time periods during each frame, thus allowing a wide range of gray scale.

In addition to LCDs, other companies are developing Digital Micro-mirror Devices (DMDs), which work by deflecting tiny mirrors (one for each pixel), thus causing light to either enter or miss a projection lens. These devices are also small and very fast, since they need to achieve gray scale in the same manner as the ferroelectric LCDs. High resolution 2048 x 1152 devices have been made in the laboratory.

Given the scope of development required to produce "fast" direct view displays to support the FSC concept and the recent emergence of suitable devices for projection systems, DTI is actively investigating the adaptation of its method to these devices.

Similar advantages can be derived when using DTI's FSC technique over competitive approaches in projection implementation. Advantages being improved display brightness, reduced frame rates and no color break up.

Three issues are being investigated in relation to adaptation of the technique to projection displays:

1) <u>The ability of microlens arrays to image spots and lines into very small pixels.</u>

   The small size of the pixels on most projection-type light valves posed questions as to whether a microlens array could image lines or spots of the small sizes required. Pixels on high resolution projector light valves possess pitches as small as 17 microns and active areas as small as 15 microns on a side. Sample microlens arrays have been obtained and experiments showed that the arrays had near diffraction limited performance. Spots of 5 microns width were successfully formed using small (1 mm diameter) fiber optic illuminators emitting light from halogen sources. The theoretical minimum possible spot size was 4 microns. Analysis showed that diffraction of light into the wrong pixels should be minimal, provided the lines or spots were centered in the pixels.

2) <u>A bright illumination system suitable for use in projection systems.</u>

   The need for a very bright light source and high throughput efficiency required investigation into illumination systems other than the fluorescent lamps used in this project. A logical line of investigation was the adaptation of standard projector light sources and illumination systems to DTI's field sequential color method. Several approaches were devised and all, in theory, would provide the light throughput efficiency and alternating R, G, B color patterns required. The most promising approach uses a moving dichroic mirror arrangement that splits light from a standard arc lamp into three colors, creating three beams of changing color that can be focused onto a small microlens array.

3) Accommodating reflective display devices.

A majority of the emerging "fast" display devices are reflective and therefore require an alternative optical arrangement from the one designed for transmissive devices.

New optical arrangements that could project the R, G, B, patterns onto the LCD pixels are being investigated. Arrangements involving the use of microlens arrays that image lines directly onto reflective pixels were analyzed, but no arrangement was found in which the arrays did not scramble the images as light passed through them on the way back out.

Arrangements in which light lines are formed at a plane separated from the light valve and re-imaged onto it via very low distortion optics were then investigated. Configurations involving conventional lenses imaging a pattern formed in a plane parallel to the array were considered feasible, (lens systems of the precision required are routinely used to make the LCDs and other arrays in the first place).

However, these arrangements involved use of a half silvered diagonal mirror to direct light into a projection lens after reflection from the light valve. Since the projection industry desires high efficiency, the half reflective mirror is considered unacceptable. The possibility of an off-axis imaging system with the precision required was investigated. Preliminary results suggest that an arrangement involving three reflective aspheric mirrors may be used for off-axis imaging with acceptable results.

It appears through preliminary investigations that adapting the DTI FSC technique to projection display devices, while challenging, is technically feasible. Given the potential performance benefits of the technique over competitive approaches, it appears commercially desirable as well.

APPENDIX B

HYDROGEN PASSIVATION OF THIN FILM TRANSISTORS FOR 180HZ DISPLAY PROGRAM

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HYDROGEN PASSIVATION OF THIN FILM TRANSISTORS FOR 180HZ DISPLAY PROGRAM

TECHNOLOGY DEVELOPMENTS REQUIRED FOR 180HZ PROGRAM

Complete success for this 180Hz program required that we advance active matrix liquid crystal display technologies in two major areas: active matrix display plate fabrication and liquid crystal assembly. The technological problems in both of these areas proved to be more difficult than originally estimated. We did, however, demonstrate that this technology choice was sound for making a field sequential display. Below we will first summarize the issues with AM fabrication and LC assembly, will describe in detail how the AM works, how plasma passivation comes into play, and finally why plasma passivation of TFTs was utilized in this program.

ACTIVE MATRIX DISPLAY PLATE FABRICATION

Prior to the start of the program we had in place a thin film transistor (TFT) fabrication process that had produced TFTs with outstanding characteristics on 4" diameter wafers. We had also made working displays on 5" x 9" glass plates. This program required that we make TFTs with very good characteristics on 5" x 9" substrates using our standard TFT "nitride passivation process" which we'll describe in some detail later.

Because we had previously had our best results on quartz, we decided to use quartz substrates for this program. This meant that the substrates were substantially more fragile than the glass, but we believed that we could accommodate this. This was a good choice, since the only major problems that we had with breakage were the result of equipment failures (at Sarnoff) and equipment set-up (at Standish), both of which would have caused even glass plates to shatter.

The TFT passivation process proved to be more of an issue. Here, prior to this program, we did not have in place equipment that would handle 5"x9" plates. During the course of the program we modified our equipment to handle this substrate size, and we improved the reproducibility of the process. Because the TFT characteristics which we were achieving for the standard "nitride passivation process" on the large quartz were marginal for this application, we believed that we had an excellent chance of substantially improving the TFT performance if we utilized large area "plasma passivation." The results of this decision were disappointing because the device characteristics for "plasma passivation" were somewhat worse than those for "nitride passivation", a very unexpected, an as yet unexplained result.

LCD ASSEMBLY

The LCD assembly process also proved to be very difficult. We went through several preliminary fabrication experiments, making cells first on small glass plates, then 5"x9" plates, and ultimately on 5"x9" plates having the AM array. Here the problem was that the "surface mode" technology had never been pushed to operate at low voltages and in an active matrix. We early-on achieved low voltage operation which was quite satisfactory. However, when used in an active matrix, the liquid crystal requirements are very severe. They depend on the chemistry of the liquid crystal material, the alignment layer, and on the underlying layers on the AM TFT substrate. In the latter case, because the liquid crystal performance is very sensitive to the angle that it makes with the surface (tilt angle) microscopic differences in the substrate condition grossly affect the liquid crystal behavior. Because of edge effects, plasma etching can cause minor differences in the way the surface is etched, and this could explain some of the non- uniform behavior that we observed in our completed displays.

HOW TFT PASSIVATION AFFECTS DISPLAY PERFORMANCE

As mentioned above, a passivation of the TFTs is required in order to make them perform satisfactorily in an active matrix array. In order to understand how this affects the display performance, we must first understand how a basic liquid crystal cell operates, what constraints are placed on the TFTs when they are used in an active matrix, how the TFTs are fabricated, and finally what the TFT passivation is and how it affects TFT performance, and ultimately the display performance.

The remaining sections of this report will go through this list in detail. It should allow the reader to understand how display excellent display performance can only be achieved when every aspect of the technology is under complete control. Over the course of this program both p-Si AM TFT fabrication and "surface mode" AM LCD assembly were evolving. Our understanding today is substantially better than it was a year ago when we were still doing the TFT fabrication and LCD assembly. Nonetheless, we achieved for this program a "local performance" that demonstrated that this technology would work, given the effort required to maintain complete process control over all the processes used in TFT fabrication and LCD assembly.

It is most likely that the only way to achieve the required process control is to fabricate the TFT plates and to do the LCD assembly in a dedicated factory environment.

THE LIQUID CRYSTAL CELL

The basic liquid crystal cell operates like an optical switch when it is placed between appropriately oriented polarizers. The liquid crystal rotates the plane of polarization of the light (as established by the input polarizer) through an angle which is determined by the voltage across the cell. The output polarizer then passes the portion of the light which polarized along its "easy axis" and rejects the remainder. Figure 1 below shows the relative orientations for the polarizer and the analyzer for the surface mode cell used in this program.

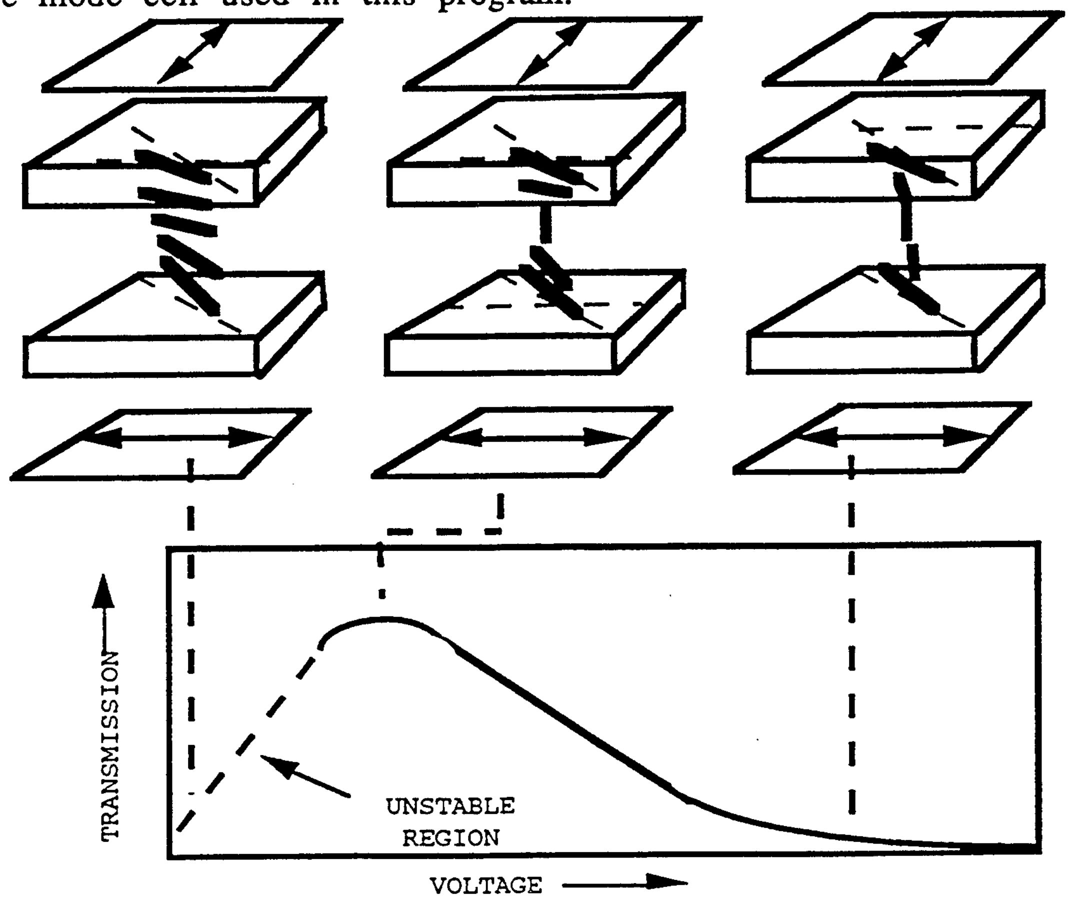

Figure 1 - "Surface mode cell" showing configuration of the liquid crystal molecules for representative voltages and the transfer curve (light output vs voltage).

Note that at low voltages all molecules are aligned parallel to the surface. At voltages above those corresponding to the peak, the LC break up into three regions: a region near the center of the gap where the molecules are vertical, and two regions near the surface where the molecules are parallel to the surface. If we stay above the peak in the transfer curve, the application of increased voltage causes these surface regions, and reduced voltages causes these regions to expand.

THE ACTIVE MATRIX:

An active matrix (AM) is required in this liquid crystal display (LCD) to a achieve high contrast ratio from the individual pixels. Although various sorts of diodes might have been used to perform the switching function of the active matrix, the more typical and highest performance active matrix employs a thin film transistor (TFT).

The ideal pixel TFT performs like a perfect switch. When a select line is addressed, every gate on that line has the "turn on" voltage applied, and every pixel along that same line is connected to the corresponding data line.

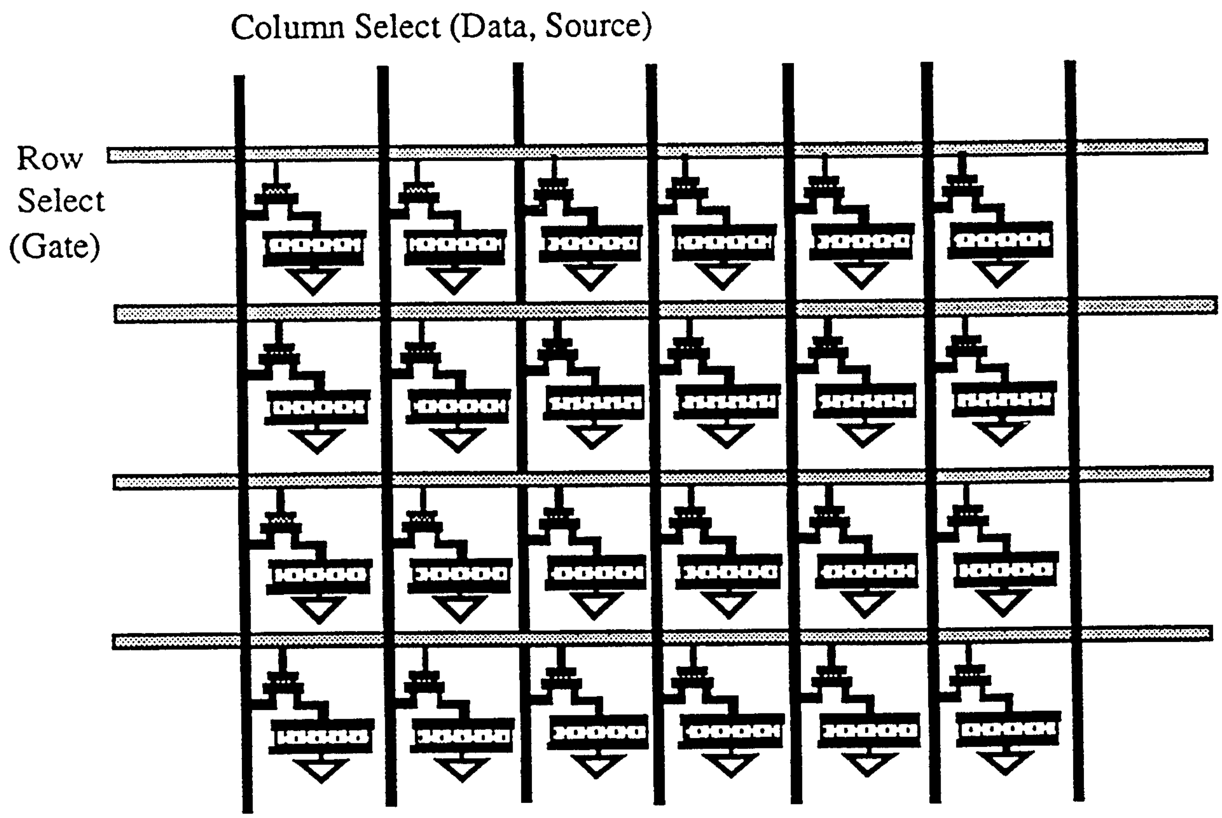

Figure 2 - Active matrix TFT array driving individual pixels, all connected to a common ground plane.

This means that when the pixel is tied to the data line through the TFT, and the TFT is on, it will come to equilibrium with the data line voltage instantaneously. When the TFT is turned off it allows no passage of current, so that the voltage will remain on the pixel for an entire frame time.

ACTIVE MATRIX REQUIREMENTS

The requirements on a TFT used in a real display are not quite so severe. Depending on the number of select lines, the refresh rate, and the required greyscale performance, we need not have infinite drive current and we will allow some leakage. This information is represented in Figure 3.

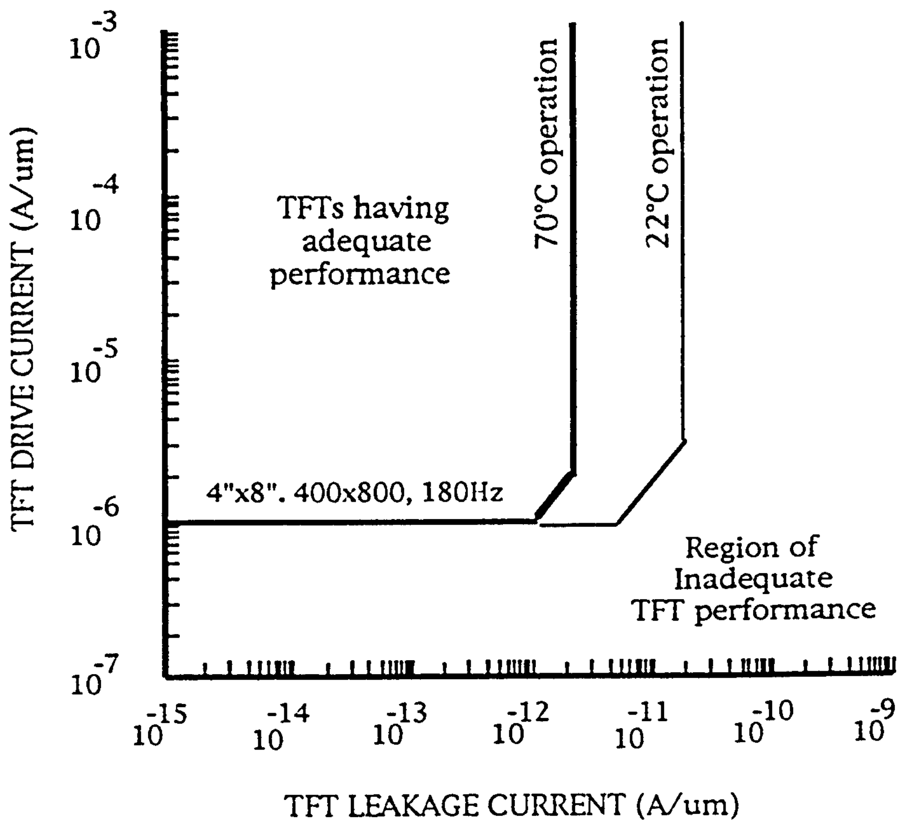

Figure 3 Performance requirements for TFTs used in an AM. Adequate performance occurs only for devices having drive and leakage in the region indicated

Figure 3 is based on an extensive analysis of the requirements for TFT drive and leakage currents for a 400x800 pixel display operating in the field sequential mode with 180 Hz frame rate. The display is assumed to have 32 gray levels when operating at a maximum temperature of either 22°C or 70°C. For each operating temperature the graph is broken into regions by a vertical and a horizontal line. The horizontal line represents a minimum limit on drive current for a given design rule (4 um in this case). This limit is primarily set by the necessity to minimize crosstalk due to stray capacitance. The vertical line represents an upper limit on leakage current that is acceptable without requiring additional pixel capacitance.

As the panels become as large as 4" x 8" other technology characteristics become as important as the transistors themselves. In particular, the RC time constants along the data and select lines become a significant problem with arrays larger than 4 in. The availability of a 10,000-Å-thick aluminum layer with a sheet resistance of only 0.03 Ω/sq. in our current p-Si process is the key to reducing the resistance along both the data and select lines. The data lines are formed with a single uninterrupted strip of aluminum, which reduces the total resistance of even a 10-in.-long line to < 1 kΩ. Along the select line, the aluminum layer is used to shunt out 97% of the sheet resistance along these lines as well. With the proper cell layout and use of the aluminum shunt, the total resistance along a 10-in. select line can be reduced to 1 < 20 kΩ despite the 20 Ω/sq. resistivity of the existing p-Si gate material.

THE POLYSILICON PROCESS

Amorphous silicon and polycrystalline silicon MOS transistors are at present the two leading candidates for use in AM LCDs. One reason that we have chosen to use p-Si transistors is that many of the process sequences that have already been proven in single-crystal silicon technology are directly applicable for use in p-Si technology. In addition, p-Si technology produces transistors with thermally grown gate dielectrics, which, in turn, produces transistors with a minimum of threshold voltage instabilities. It should be noted that, because of the compatibility between single-crystal silicon processing and polycrystalline silicon processing, p-Si transistors are also being used in bulk silicon VLSI circuits in such applications as load transistors in static memories. The cross section of such a p-Si TFT is shown in Figure 4.

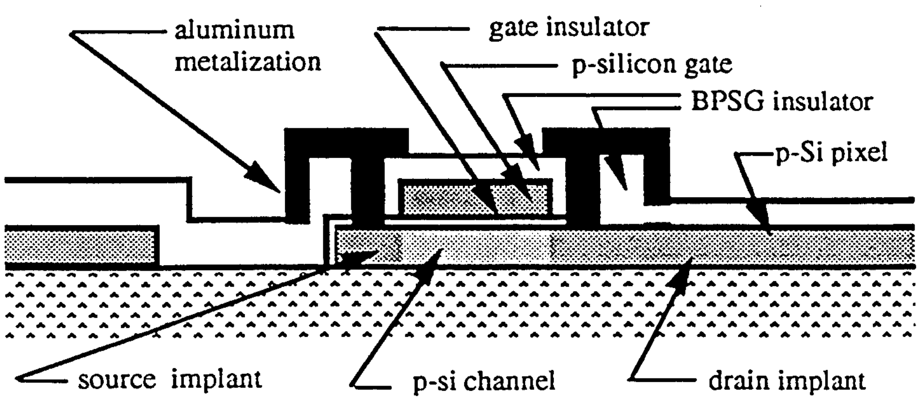

Figure 4 - Cross section of an AM TFT plate showing p-Si pixel

Figure 5 below shows the general process that is used to fabricate the p-Si thin film transistors. In order to maintain tight dimensional control, the quartz substrates upon which the TFTs are fabricated must first be annealed. After annealing the substrates, a layer of low-temperature LPCVD silicon is deposited. The p-Si film thickness is chosen as a compromise between thicker films, which produce transistors with higher mobility, and thinner films, which produce transistors with lower leakage currents. When this p-Si film also serves as the pixel electrode its thickness needs to be as thin as possible. Additional steps are indicated on the diagram.

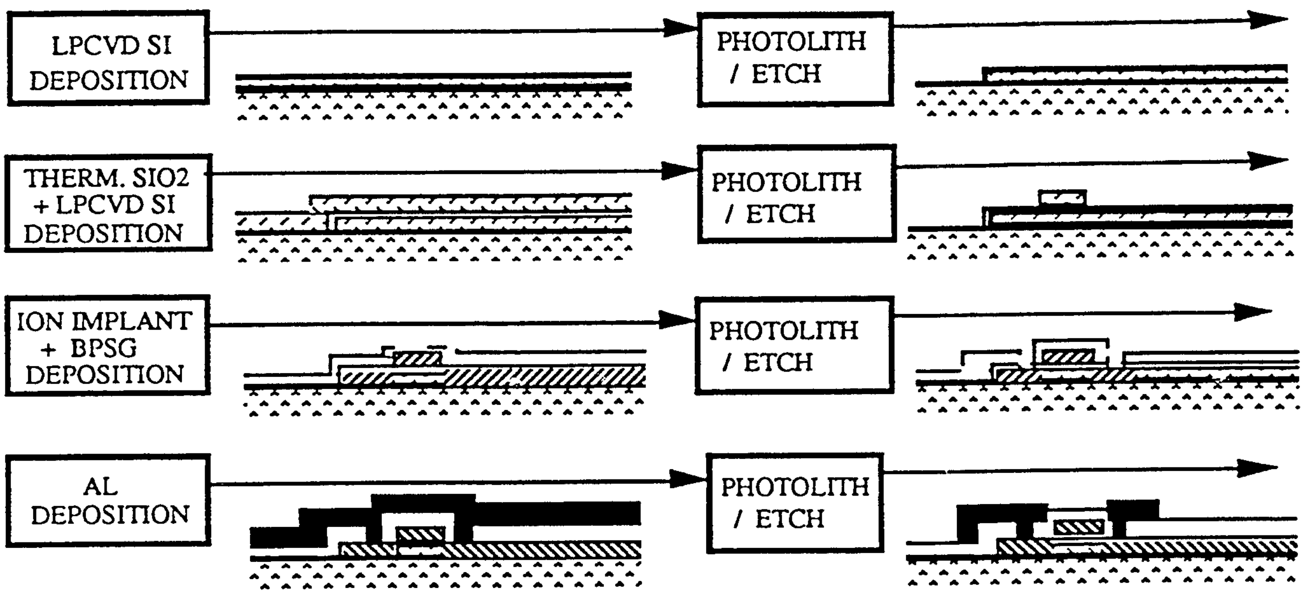

Figure 5 - Principal steps in the fabrication of p-Si AM TFTs.

HYDROGENATION

The one major step that is not called out in this sequence is the hydrogenation passivation process. This process is required because, as deposited and annealed, p-Si has a number of dangling bonds, bonds that would ordinarily connect to Si atoms together in a perfect crystal but which are simply not connected in the disordered array of Si atoms near the edges of the p-Si grains, i.e. at the grain boundaries. If these dangling bonds are left as fabricated, they serve as traps for charge. This leads to both low drive current and high leakage current. To cure this problem for p-Si, hydrogen must be introduced into the active area of the Si (the first layer shown on the above diagram) after the complete TFT fabrication process is completed. This can be done in several ways: nitride passivation the traditional process used by Sarnoff and plasma passivation, a newer development in the p-Si process.

NITRIDE PASSIVATION

In nitride passivation we first deposit by PECVD a layer of Si3N4 over the BPSG in a manner that incorporates a significant amount of hydrogen into the film. After the process is completed, the plates are heated and some of the hydrogen is driven into the TFTs. This is a very simple process, but it is not very controllable. We have never achieved the best results, because the TFTs so passivated do not have the lowest leakage or the highest drive possible given the starting material.

PLASMA PASSIVATION

An alternative approach which has been under investigation for several years at Sarnoff, is to completely fabricate the plate and then put it back into a plasma system. By appropriate choice of reaction gases, power, substrate temperature and time we are able to drive hydrogen from the plasma back into the substrate. Although this procedure has in principle complete control over the amount of hydrogen introduced into the TFTs, it requires very tight controls over the conditions of the plasma.

PREVIOUS RESULTS

As mentioned earlier, we had previously worked on 4" diameter quartz substrates and had demonstrated the improved performance of plasma passivation of TFTs compared with the nitride passivation. This is shown dramatically in Figure 6 below.

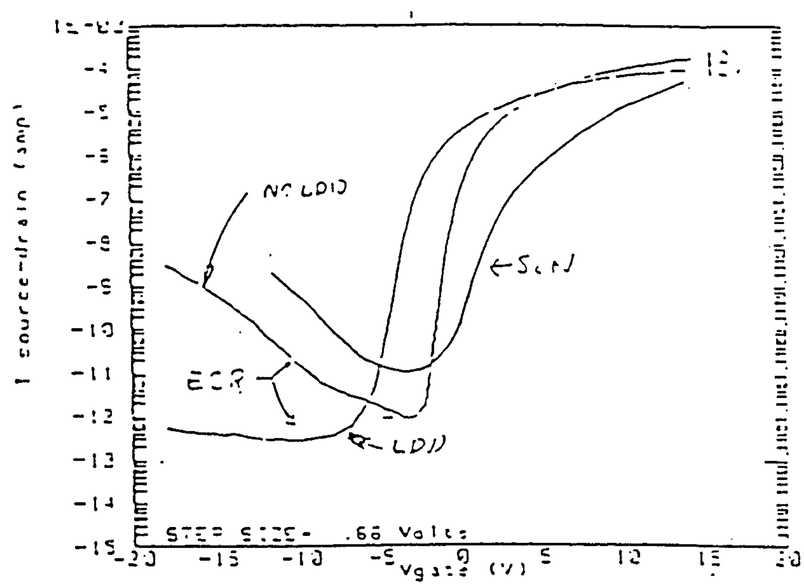

Figure 6 - Performance of TFTs processed on 4" diameter quartz wafers.

Note that the present program incorporated a lightly doped drain (LDD) which causes the leakage current to remain flat as we decrease the voltage to perhaps 10 - 15 volts below 0, also as shown on Figure 6. This LDD is a region of the drain, immediately adjacent to the gate, which is masked during the ion implantation step so that it does not get the drain implant.

If we now plot the data from the 4" diameter wafers on the required performance chart for TFTs we obtain the graph shown as Figure 7. Note that all processes produced devices with a drive current greatly exceeding the requirements. The nitride passivated devices have a leakage current that is marginally too high at negative gate voltages to satisfy the present requirements. However, with a LDD this process too should be capable of achieving the required performance.

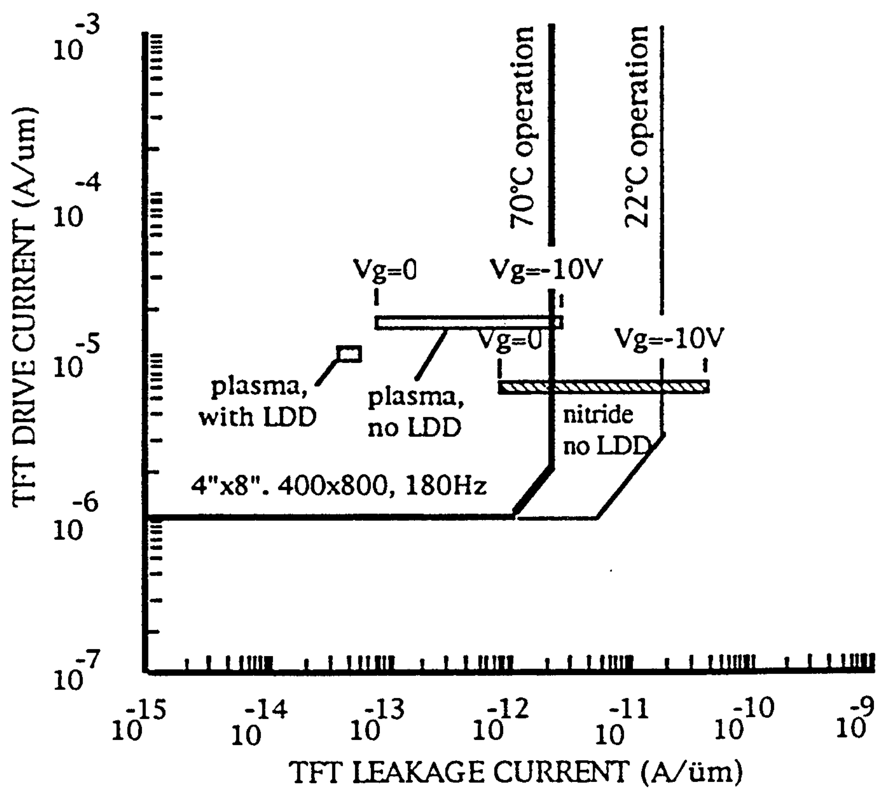

Figure 7 - Data from Figure 6 plotted on TFT performance requirements chart.

Note that for the plasma passivated TFTs with a lightly doped drain (LDD) the leakage is approximately constant for negative gate voltages. The devices without LDD have a range of leakage current shown. The minimum leakage occurs at approximately 0 Volts while the maximum leakage shown is that which occurs at approximately -10 Volts.

PRESENT RESULTS

The transistor characteristics for devices processed under the two present field sequential programs were similar to those shown in Figure 6. Note that the characteristic is flat for negative gate voltages, a result of the LDD structure. These data are for a device having a gate length of 8 microns and a gate width of 4 microns. The previous graph shown as Figure 6 is for devices having a 10 micron gate width.

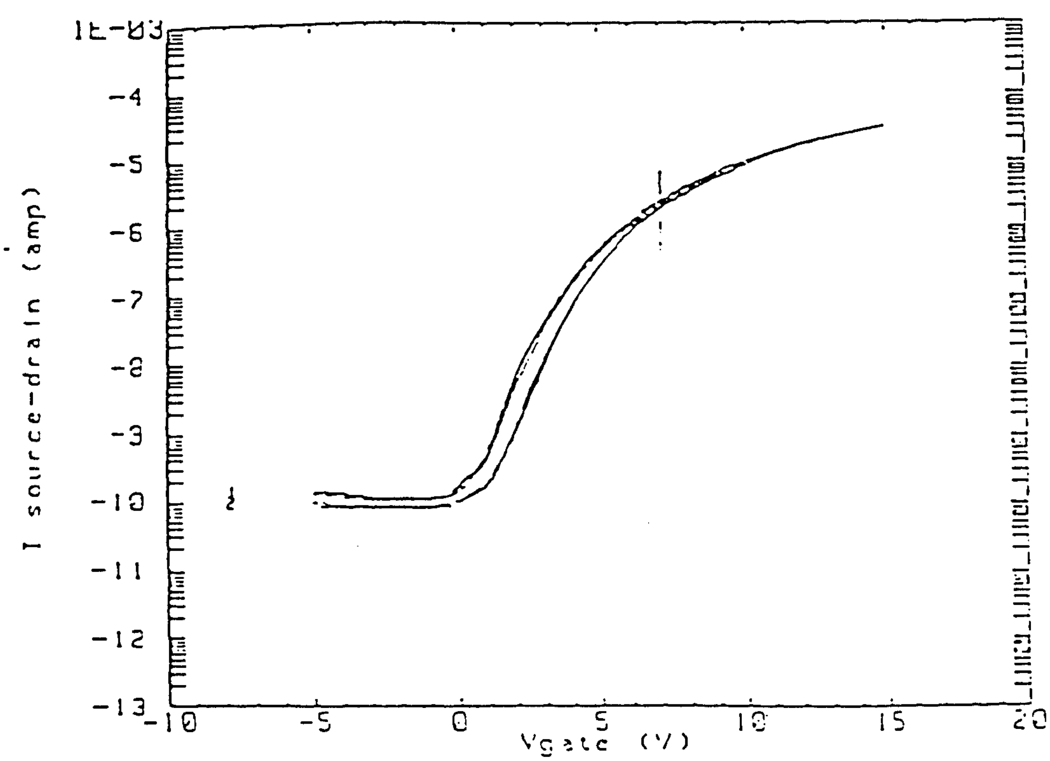

Figure 8 - Device characteristic of TFT processed on large quartz substrate.

The results for the present program are best summarized as Figure 9 below which shows both drive and leakage currents measured on test TFTs the plates that were considered for assembly and normalized to 1 micron gate width. Here the "drive current" is measured at a gate voltage of 15 Volts and the "leakage current" is measured in the flat region of the characteristic below 0 Volts. In fact, it is difficult to control TFT process so that the gate voltage for which the TFTs turn off is precisely 0, but our system provided an adjustable voltage to compensate for

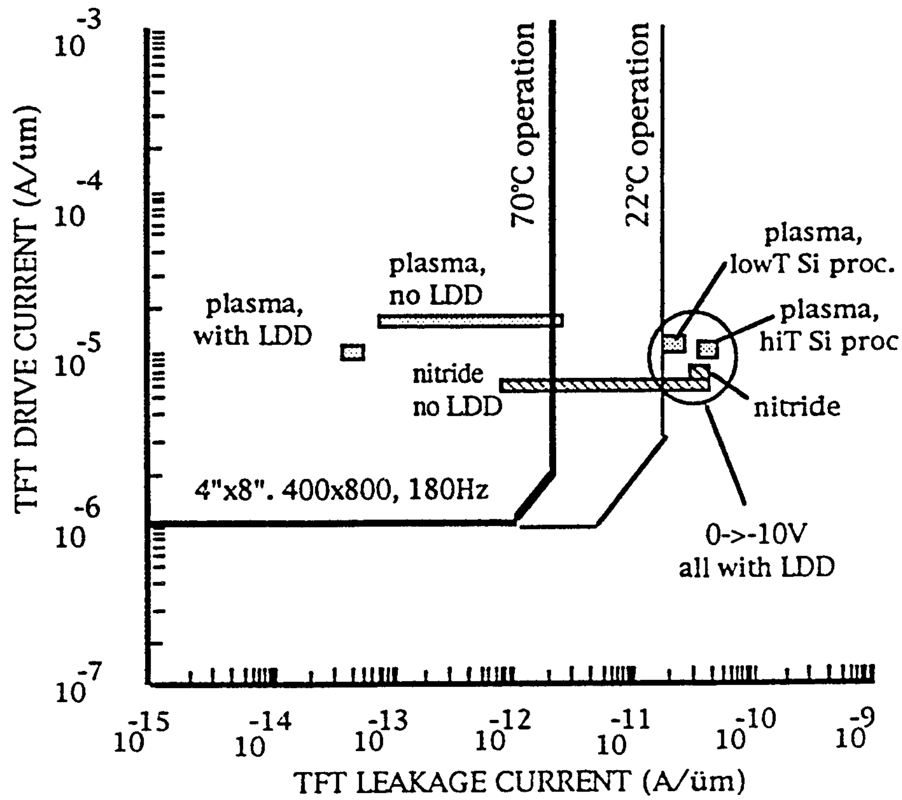

Figure 9 - Performance of TFTs fabricated in present program compared with previously processed devices. Those processed in the two present programs are snown in the ellipse

Note that the TFTs have adequate drive but have a leakage that is too high to maintain an accurate 5 bit greyscale at elevated temperature. The measured performance of the TFTs in the displays for relatively low temperature operation was consistent with the predictions in the above graph. In fact, some devices performed quite satisfactorily with no noticeable drop in voltage across the pixel in a 1/150 sec frame time. Other devices were not nearly as good, for reasons not yet understood.

It is likely that the poor performance observed on some displays is due to a combination of TFT leakage (as determined by the measurements which are always taken on test devices near the edge of the panel), TFT leakage nonuniformity (which could be caused by a number of factors in this complicated processing sequence but which may not show up in the measurements of test devices at the perimeter of the panel) and LCD leakage (which has not been adequately characterized for the process that we used to fabricate these"surface mode" devices). Controlling each of these factors could be goals for future research programs. Nonetheless, we have demonstrated locally the feasibility of this approach, which is a substantial achievement.